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(71) Applicant: RESOUND CORPORATION [US/US]; 220 Saginaw Drive, Seaport Centre, Redwood City, CA 94063 (US).

(72) Inventor: TAENZER, Jon, C.; 888 Laverne Way, Los Altos, CA 94022 (US).

(74) Agent: KREBS, Robert, E.; Burns, Doane, Swecker & Mathis, L.L.P., P.O. Box 1404, Alexandria, VA 22313-1404 (US).

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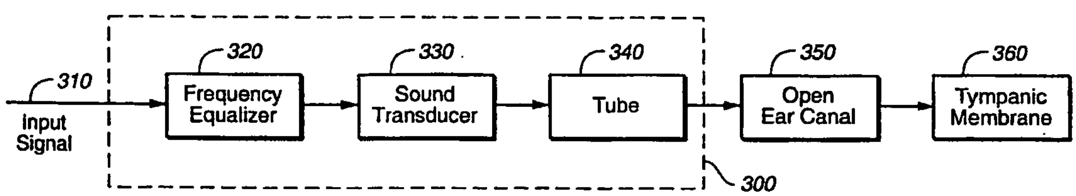

(57) Abstract

The invention relates to an open-canal communication device (330) and method for processing sound that is delivered directly in a user's open ear canal (350), so that the user will perceive the sound to have a high quality and a flat frequency response. This is accomplished by enhancing sound intensities (320) at frequencies below the ear canal resonance frequencies, reproducing sound in the canal resonance frequency bands with a flat response, and enhancing sound intensities at higher frequencies.

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HIGH QUALITY OPEN-CANAL SOUND TRANSDUCTION DEVICE AND METHOD

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to sound reproduction, and particularly to sound reproduction in a user's ear canal.

2. State of the Art

Some users require two way communication devices that allow them to hear both electronically transmitted signals and open air sounds, and that are compact, discreet and convenient. Open air sounds, also known as free field sounds, are sounds that are present in the air and outside a person's ear. For example, U.S. Secret Service agents assigned to covertly protect individuals require two way communications systems that are unobtrusive and allow them to both clearly communicate with remote locations and accurately perceive local, open air sounds. Conventional two way communications systems used in such situations and conventional hearing aid technologies typically provide sound directly to a user's ear canal via in-ear speakers that occlude the ear canal. One reason for occluding the ear canal is to prevent output of the in-ear speaker from generating positive feedback with a microphone located near the user's ear.

In contrast, open air sound transmissions and conventional earphone technologies typically deliver sound to a user's pinna, the outer projecting portion of the ear. A user will perceive sound delivered to the user's ear via conventional earphone technology differently from sound delivered to the user's ear via conventional in-ear hearing aid technology, because the pinna enhances higher frequency components of the sound. In addition, in-ear speakers and/or hearing

aids which typically occlude the ear canal, alter the resonance properties of the ear canal and further accentuate the difference in sound quality perceived by the user. Consequently, conventional hearing aid technologies and techniques typically adjust sound volume and frequency response so that the user will perceive sounds as having a high quality and a flat frequency response, as if they were open air sounds. In-ear speakers and/or hearing aids which occlude the ear canal are also subject to other disadvantages. For example, by occluding the ear canal they prevent the user from hearing important ambient or environmental sounds. In addition, occluding the ear canal causes the user to hear his own voice differently. Some of the sound energy of the user's voice travels through the bones of the user's head into the user's ear canal. Under normal circumstances, i.e., when the ear canal is unoccluded, a portion of this sound energy (which is composed primarily of lower frequencies) escapes out of the ear canal into the free field. However, when the ear canal is occluded near the opening, the sound energy that would otherwise have escaped instead travels to the tympanic membrane. Thus, the result at the tympanic membrane is that the lower frequencies of the user's voice are unnaturally enhanced, which is often found to be disturbing and/or distracting to the user.

Recently, in-ear speakers and hearing aids have been contemplated that do not occlude the ear canal, and which are often referred to as "open-canal" devices. However, when conventional hearing aid technologies and techniques for adjusting sound volume and frequency response are used with open-canal devices, sound quality as perceived by the user is typically unsatisfactory. Accordingly, it would be desirable to provide an open-canal speaker or hearing aid that adjusts sound volume and frequency response so that a user will perceive sounds transmitted by the speaker as having a high quality and flat frequency response.

SUMMARY OF THE INVENTION

The present invention is directed to an open-canal communication device and method for processing and delivering sound to directly to a user's open ear

canal, so that the user will perceive the sound to have a high quality and a flat frequency response.

Exemplary embodiments of the invention emit sound in the user's open ear canal, and variously perform the following functions. First, sound intensities at frequencies below the ear canal resonance frequency are enhanced to properly compensate for a loss of sound energy into the room or air space surrounding the user's ear, which increases with the wavelength of the sound. Second, in accordance with the recognition that the open-canal configuration can leave natural resonance properties of the user's ear canal substantially undisturbed, sound intensities in the canal resonance frequency bands are reproduced with a flat overall response with respect to the canal resonance. Third, since sound provided directly to a user's ear canal bypasses the user's pinna, sound intensities at high frequencies are enhanced to properly emulate the pinna's intensity enhancement of high frequency free field sound. Thus, according to the invention electronically transmitted sound is processed and reproduced in the ear canal using an open-canal speaker or transducer to provide sound that a user will perceive as having a high quality and a flat frequency response.

In accordance with embodiments of the invention, sound is provided near the entrance of the user's ear canal, for example just inside the ear canal entrance, by a mechanism such as a slender tube or a speaker driver housing that does not occlude the ear canal. The mechanism does not significantly disturb the natural resonance of the ear canal, and minimally attenuates ambient sounds that enter the ear and pass through the ear canal to the tympanic membrane. For example, the attenuation of ambient sounds due to the presence of the mechanism can be on the order of 1 dB or less, an attenuation which (as described further below) is imperceptible to the average user.

Advantages of the invention include improved quality of sound generated by open-canal devices used in hearing aids and two way communication systems. Other advantages include greater simplicity and corresponding reductions in cost

and size. The present invention can be used with in-ear, open-canal hearing aids and with in-ear, open-canal two way communication systems. For example, the present invention can be used in conjunction with the hearing aid described in copending U.S. Application Serial No. 08/781,714, filed in the U.S. Patent and Trademark Office on January 10, 1997 and hereby incorporated by reference. The present invention can also be used with, for example, the ear-level voice pickup disclosed in copending Application No. ______________, entitled "Dual Modality High Quality Ear Level Voice Pick-Up" [Attorney Docket No. 022577-403], and can also be used with, for example, the microphone and method disclosed in copending Application No. ___________, entitled "Ear Level Noise Rejection Voice Pick-Up Method" [Attorney Docket No. 022577-405], both of which are hereby incorporated by reference.

BRIEF DESCRIPTION OF THE DRAWINGS

Other objects and advantages of the present invention will become apparent to those skilled in the art from the following detailed description of preferred embodiments, when read in conjunction with the accompanying drawings. Like elements have been designated with like reference numerals.

FIG. 1 is a graph showing a characteristic Shaw transfer function, and component curves that make up the transfer function.

FIG. 2 is a graph showing sound pressure measured at a user's tympanic membrane that corresponds to a flat frequency response sound provided at the entrance of a user's ear canal.

FIG. 3 is a block diagram of an embodiment of the invention.

FIG. 4 is a graph showing a curve that represents a simulated, closed-canal output of a Knowles EP-7110 transducer, as would be measured at a tympanic membrane.

FIG. 5 is a graph showing a curve that represents a measured equivalent free field output of the Knowles EP-7110 transducer.

FIG. 6 is a graph showing a set of curves that represent equivalent free field outputs of a Knowles CI-8204 speaker driver with each of five lengths of plastic tubing.

FIG. 7 is a graph showing the curve from FIG. 6 that represents the equivalent free field output of the Knowles CI-8204 speaker driver with a 3.25" length of plastic tubing.

FIG. 8 is schematic circuit diagram of a passive equalizer circuit for use in a first preferred embodiment of the invention.

FIG. 9 is a graph showing a curve that represents an ideal equalization characteristic.

FIG. 10 is a graph showing an equalization characteristic of the circuit shown in FIG. 8.

FIG. 11A is a graph showing an overall equivalent free field measured response of the first preferred embodiment of the invention.

FIG. 11B is a graph showing the output of the first preferred embodiment as measured at the tympanic membrane, in comparison with a target response measured at the tympanic membrane.

FIG. 12 is a graph showing a response characteristic a Knowles ED-1932 transducer as measured in a simulated closed canal situation.

FIG. 13 is a graph showing a set of curves that represent equivalent free field sound outputs of the Knowles ED-1932 speaker driver with each of five lengths of plastic tubing.

FIG. 14 is a graph showing the curve that represents the equivalent free field output of the Knowles ED-1932 speaker driver with a 2.50" length of plastic tubing.

FIG. 15 is a graph showing an equalization characteristic of an active equalizer for use with a second preferred embodiment of the invention.

FIG. 16A is a graph showing an overall equivalent free field measured response of the second preferred embodiment of the invention.

FIG. 16B is a graph showing the output of the second preferred embodiment as measured at the tympanic membrane, in comparison with a target response measured at the tympanic membrane.

FIG. 17 is a graph showing a non-equalized, free field equivalent response of a third preferred embodiment of the invention without tubing.

FIG. 18 is a circuit diagram of an equalizer for use with the third preferred embodiment of the invention.

FIG. 19 is a graph showing an equalization characteristic of an active equalizer for use with the third preferred embodiment of the invention.

FIG. 20A is a graph showing an overall free field equivalent response of the third preferred embodiment of the invention.

FIG. 20B is a graph showing the output of the third preferred embodiment as measured at the tympanic membrane, in comparison with a target response measured at the tympanic membrane.

FIG. 21 is an enclosure for a voice-coil transducer.

FIG. 22A is a graph showing an overall free field equivalent response of the fourth preferred embodiment of the invention.

FIG. 22B is a graph showing the output of the fourth preferred embodiment as measured at the tympanic membrane, in comparison with a target response measured at the tympanic membrane.

FIGS. 23A-C show an earpiece that can incorporate an embodiment of the invention.

FIGS. 24A-C show an earpiece that can incorporate an embodiment of the invention.

FIGS. 25A-B show an earpiece that can incorporate an embodiment of the invention.

FIGS. 26 and 27 show an earpiece that can incorporate an embodiment of the invention.

FIG. 28 shows, for example, an acoustic damper for use of the present invention.

FIG. 29 is a cross-sectional view of a section of acoustic tubing for use of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 3 shows a block diagram of an open-canal communication device 300 in accordance with the invention. The communication device 300 receives a signal representing an open air sound via an input line 310, which conveys the signal to a frequency equalizer 320, a sound transducer 330, and a tube 340. An output of the frequency equalizer 320 is provided to the sound transducer 330, which generates sound for delivery to a user's ear canal 350. The sound generated by the sound transducer 330 is provided to one end of the tube 340, and is emitted at the other end of the tube 340. The tube end from which the sound is emitted is located near the opening of the user's ear canal 350, preferably just inside the canal opening. Thus, equalized sound is provided directly to the user's open ear canal 350, and travels down the canal 350 to the user's tympanic membrane 360. The tube 340 can be omitted, and the transducer 330 can be located in the ear canal.

FIG. 1 shows sound levels measured at the tympanic membrane of a typical user's ear, that correspond to a free field, flat-frequency response sound source, or in other words, a sound source in free field that has a constant intensity across all frequencies. In particular, FIG. 1 shows a graph having magnitude in decibels (dB) on the vertical axis and sound frequency in Hertz (Hz) on the horizontal axis. Given an open air or free field sound signal whose intensity is the same across all frequencies, the Shaw curve 100 shows how that sound signal appears at the tympanic membrane of the typical person's ear after being gathered by the user's outer ear, and traveling down the user's ear canal to the tympanic membrane. If a sound signal having the shape of the Shaw curve 100 occurs at the user's tympanic

membrane, then the person will perceive that sound to be an open air sound signal whose intensity is the same across all frequencies.

With respect to the Shaw curve 100, the shape of the curve, i.e., the transfer function of free field sound to sound at the user's tympanic membrane, will vary depending on the direction or azimuth the sound is coming from, as well as the elevation or height of the sound source. The curves 102, 104 and 106 show individual contributions to the tympanic membrane frequency response due to a free field sound source located at +45° azimuth. Depending upon the application, designers often aim to achieve a match to different target responses or different versions of the Shaw transfer function whose differences depend on orientations of the sound source with respect to a user's ears. For example, a diffuse-field transfer function which is an average of responses over many angles, can be used. Headphones intended for the audiophile are often designed to reproduce a diffuse-field response at the tympanic membrane when driven with a flat frequency response electrical signal, so as to recreate the sound of a reverberant theater. The embodiments described below use as a target the free field to tympanic membrane transfer function at 0° azimuth, which best represents the sound of a person standing about a meter straight in front of the user. Of course, other transfer functions can be used in various embodiments of the invention, depending on such factors as intended environment, engineering and/or cost constraints, and the like.

As shown in FIG. 1, the Shaw curve 100 is the sum of several different contributions, including the contribution 102 of the natural resonance of the user's ear canal; an enhancement 104 provided by the user's outer ear; and an enhancement 106 provided by the user's body. The outer ear enhancement 104 is a combination of effects of the user's pinna and concha, and the effects are collectively referred to as the "pinna effect". The ear canal resonance enhancement near 2.5 kHz, and the pinna effect enhancement near 5 kHz strongly affect the perceived naturalness and quality of a sound.

In devices such as headsets, earphones, earbuds, telephone receiver systems and the like, it is desirable to compensate for any alteration in function of the user's ear, so that an overall transfer function that relates a free field sound which the device is intended to recreate to a corresponding sound measured at the user's tympanic membrane, is as close as possible to the Shaw curve 100. The closer the transfer function is to the Shaw curve 100, the more the user will perceive the transmitted sound to be "natural" or of "high quality". As a practical matter, the smallest change in sound intensity that a typical person can perceive is about 3 dB, so intensity variations of the transfer function from the Shaw curve 100 that are less than 3 dB will generally not cause a user to perceive a difference in sound quality.

Furthermore, where the transfer function differs from the Shaw curve 100 by falling off below about 250 Hz and above about 5 kHz, these falloffs will not substantially affect intelligibility of speech reproduced by a sound processing system using the transfer function. This is because the majority of sound necessary for speech to be intelligible lies in the frequency range between 300 Hz and 3 kHz. Furthermore, the ability of a sound processing system to accurately reproduce sounds below 300 Hz and above 3 kHz is generally useless when the sound processing system is used in a conventional telecommunication system, because conventional telecommunication systems typically transmit only sounds between 300 Hz and 3 kHz.

This is because the bandwidth of 300 Hz to 3 kHz was selected as a result of extensive research in the earlier part of this century by Bell Telephone, in response to efforts to determine a minimum bandwidth that would provide voice communications having an acceptable level of sound quality and intelligibility. Thus, the frequencies below and above this range are discarded and not transmitted, in order to minimize the bandwidth of a voice conversation and thus the amount of telecommunication resources necessary to transmit the conversation.

Thus, when embodiments of the invention are used with conventional telecommunications systems which do not transmit frequencies below 300 Hz and above 3 kHz, outputs below 250 Hz and above 5 kHz are moot and thus can provide additional design flexibility so that overall device performance can be more easily balanced against complexity and expense, subject to practical engineering constraints.

Other embodiments of the invention can have different frequency ranges. For example, embodiments intended for use in hearing aid applications can have a frequency range from about 200 Hz to about 6 kHz, embodiments intended for use in multimedia applications can have a frequency range of 50 Hz to 10 kHz, and embodiments intended for high-fidelity use can be configured to have a frequency range that is similar to that reproduced from a compact disc (CD), i.e., from about 30 Hz to about 16 kHz. In general, embodiments of the invention can be configured to have different frequency ranges depending on particular applications and intended operating environments.

As shown in FIG. 2, when a transducer provides a flat frequency response sound at the entrance of the user's open ear canal, corresponding sound measurements at the user's tympanic membrane will have the curve shape 200. The curve shape 200 has a low frequency dropoff of about 12 dB per octave, which indicates that sound energy from the transducer is lost into the open air or free field surrounding the user's ear. This loss occurs because some of the sound energy emitted by the transducer travels out of the ear canal and into the free field, instead of through the ear canal to the tympanic membrane. The curve shape 200 also indicates that the pinna effect near 5 kHz has been lost, which happens because sound provided at the entrance to the ear canal bypasses the outer ear. The canal resonance enhancement near 2.5 kHz remains because the ear canal is open and not occluded, and its resonance properties are not substantially affected.

Accordingly, in this situation to properly recreate the curve 100 or a curve similar to it, but for a 0° azimuth, the pinna effect must be restored and the low

frequency loss must be compensated for. In addition, any significant non-linear characteristics of the transducer must also be compensated for to assure that harmonic distortion (e.g., total harmonic distortion, THD) and intermodulation distortion (IMD) do not degrade the sound quality.

Preferred embodiments of the invention described below include: 1) a very high sound pressure level (SPL) passive delivery system, that is designed for discreet use by personnel who require reliable communications in high ambient noise conditions, for example, law enforcement agents and firemen; 2) a moderate SPL delivery system for discreet use in business applications such as cordless and cellular telephony; 3) a tiny, lower output, active delivery system for consumer and small-office or home-office applications; and 4) a low cost, passive delivery system based on an earbud-type voice-coil speaker driver for use in consumer applications where minimizing cost is of paramount concern.

The following design rules and possibilities can also be used to ensure satisfactory device performance. First, a speaker driver is selected that is capable of moving enough air to satisfy product requirements without reaching non-linear portions of its performance envelope (which would create unacceptable distortion). The speaker driver should also be sufficiently inexpensive, and should have an impedance that is compatible with other elements in the device and/or the signal source, such as a radio, hearing aid circuit, CD player or the like. The speaker driver should also match the available electrical drive power and satisfy any size requirements of the design. Second, the acoustic system portion of the device is designed according to the method described below to achieve the best compromise between bandwidth, SPL output, and response flatness characteristics (as measured at the tympanic membrane and corrected for by the free field target response). Third, electronic equalization is used to tune the device response to within a specified tolerance of the target response.

The first, second and third preferred embodiments use as their sound transducers or speaker drivers that are commonly used in conventional hearing

aids, while a fourth preferred embodiment uses a standard off-the-shelf earbud speaker driver. The sound transducers used in conventional hearing aids are commonly referred to as "receivers". There are several major differences between these two types of drivers. First, conventional hearing aid receivers are typically designed using variable reluctance, balanced armature "motors", while earbud speaker drivers typically use voice-coil "motors". Second, variable reluctance motors are more efficient in converting electrical energy into sound energy than voice-coil motors, and can be smaller in size. Third, variable reluctance motors are self-limiting, and are thus more reliable and have lower distortion. Fourth, voice-coil motors are less expensive and more widely available. Fifth, voice-coil motors can generally move more air than variable reluctance motors, and therefore reproduce lower frequency sounds more effectively. Generally, variable reluctance motors are used in products where small size and efficient energy usage are more important than low cost, while voice-coil motors can be effectively used in low-cost and multimedia applications.

Furthermore, the performance of hearing aid receivers in different conditions must be considered in the design process. For example, FIG. 4 shows a response curve 400 for a Knowles EP-7110 hearing aid receiver under simulated closed-canal conditions. The closed canal condition can be simulated by connecting the EP-7110 hearing aid receiver to a coupler having an air volume of 2 cubic centimeters (cc's). In contrast, the Knowles EP-7110 hearing aid receiver has a different response curve 500 when its output is measured in a free field situation, as shown in FIG. 5. In accordance with embodiments of the invention, the user's ear canal is not occluded and thus the curve 500 is more useful than the curve 400 in the design process. Specifically, the curve 500 shows that the bass or low frequency response falls off at about 12 dB per octave, because there is no closed volume to capture the pressure generated by the EP-7110's speaker driver. In addition, the fundamental electroacoustic resonance has moved up to 3.3 kHz. The resonance peak at 2.5 kHz of the curve 400 is lower than the 3.3 kHz of the curve

500 because of the additional mass loading on the driver's diaphragm due to the trapped volume of air created by the 2-cc coupler load. The high frequency response of the curve 500 is also extended with respect to the curve 400.

In the first preferred embodiment, a high output, small and highly efficient hearing aid receiver such as the Knowles CI-8204 variable reluctance motor device with a 400 ohm winding is used. This receiver has its electroacoustic response intentionally tuned by its manufacturer to occur at approximately the same frequency as a user's ear canal resonance frequency. In hearing aids, this tuned response is used to replace the natural ear canal resonance enhancement that is lost because the hearing aid occludes the ear canal, destroying that resonance.

In the first preferred embodiment, most of the device is discreetly located behind the user's ear. A clear plastic tube conveys sound from the device to the user's ear canal entrance. Thus, the speaker driver of the CI-8204 device is acoustically loaded with the tube, which is open at the end located near the ear canal entrance. This construction forms a Helmholz resonator. In other words, the compliance of the volume of air within the receiver housing, working in conjunction with the mass of air in the tube, forms a resonator that enhances the intensity of sound whose frequency is at or near the resonant frequency of the resonator.

In the first preferred embodiment, the Helmholz resonator is designed so that the resonant frequency is well below the bass falloff frequency of 2.5 kHz shown in FIG. 2. For example, the Helmholz resonant frequency can be tuned by changing the length and/or inner diameter of the clear plastic tube. Once the hearing aid receiver is chosen, the speaker driver's air volume is predetermined and unchangeable, so tubing length becomes the dominant determinant of the Helmholz resonant frequency. Changes to the inside diameter of the tubing have only a small, second order effect on the resonant frequency, but do have a large effect on the loudness of the resulting output. Thus, the inside diameter of the

tubing can be chosen primarily to meet the maximum output requirements of the design, and to satisfy aesthetic considerations.

The Helmholz resonance is strong enough so that the overall design can provide the necessary compensation of over 23 dB at 500 Hz that is indicated in FIG. 2, and thus achieve a flat frequency response down to 500 Hz, yet still provide a sufficiently large output. Another advantage is that the Helmholz resonance effect falls off at 12 dB per octave above the Helmholz resonance peak, or above the Helmholz resonant frequency, which precisely matches and compensates for the opposite 12 dB per octave falloff (shown in FIG. 2) that results from providing the sound at the ear canal entrance, where some of the sound energy is lost into the free field.

FIG. 6 shows the free field equivalent output of the CI-8204 device as measured at the tympanic membrane and corrected for the target Shaw response curve for 0° azimuth, when connected with each of five lengths of plastic tubing having an inner diameter 0.058 inches.

The "free field equivalent output" as used here and elsewhere in this document, specifically means a free field sound that, after being captured by a user's outer ear and passing through the user's open ear canal and arriving at the user's tympanic membrane, has the same frequency response profile at the tympanic membrane as does the sound emitted by the open-canal communication device when it arrives at the tympanic membrane, where the sound emitted by the open-canal communication device is based on a signal representing a free field, flat frequency response sound. Thus, when the open-canal communication device emits a sound into the user's ear canal opening that is based on an electronic signal representing a free field, flat frequency response sound, the user will perceive the signal as a free field sound having the frequency response profile of the free field equivalent output.

For example, the curve 1100 of FIG. 11A is the profile of a free field sound that, when it reaches the tympanic membrane after being gathered by the

outer ear and passing through the ear canal, will arrive at the tympanic membrane, and at the tympanic membrane will have the same profile as the curve 1120 shown in FIG. 11B. When the open-canal communication device emits a sound that is based on an electronic signal representing a free field, flat frequency response sound, the emitted sound will travel through the ear canal and arrive at the tympanic membrane. When it arrives at the tympanic membrane, it will have the same profile as the curve 1120, and the user will perceive it to be a free field sound having the profile 1100. Thus, a free field equivalent output curve provides an accurate and intuitive picture of the characteristic behavior of a corresponding open-canal communication device.

With respect to FIG. 6, the curves 604, 602, 600, 606, and 608 represent the free field equivalent output of the CI-8204 device when used with tubing having lengths of 3.75 inches, 3.5 inches, 3.25 inches, 3.0 inches and 2.75 inches respectively. FIG. 7 shows only the curve 600 so that its shape can be easily seen.

The peaks of the curves in FIG. 6 occurring between about 600 Hz and about 900 Hz are due to the Helmholz resonance, and clearly show how the resonance frequency changes with tubing length. Since the inner diameter of 0.058 inches is a relatively large inner diameter, there is little friction created by the air moving through the tubes and therefore the Helmholz resonance peak is high and not well damped. Acoustic dampers can be added to the "acoustic plumbing" design to flatten the response, but such dampers can significantly reduce output. For a high output system like that of the first preferred embodiment, electronic equalization is used instead of acoustic damping and will be described further below.

As shown in FIGS. 6 and 7, the tubing also produces additional response peaks and valleys. These are caused by the "organ pipe" effect, wherein any pipe or tube that is closed at one end will have resonant response peaks at frequencies where the length is $N \cdot \lambda \cdot 1/4$, where N is any odd, positive integer and λ is the acoustic wavelength in the tubing. Resonant valleys will occur at frequencies

which have a wavelength λ where the tubing length is $N \cdot \lambda \cdot \frac{1}{2}$, where N is any positive integer. The higher frequency peaks shown in FIGS. 6 and 7 are primarily caused by these tubing resonances or organ pipe effects, and are a direct function of tubing length. Accordingly, by choosing the tubing length appropriately, one of the tubing's resonant valleys can be placed at the same frequency as the electroacoustic peak of the CI-8204 device, thereby reducing its height, flattening the overall free field equivalent response of the system, and reducing an amount of electronic equalization that is necessary or desirable. By judiciously choosing the tubing length, a relatively flat open ear response can be achieved, even without using electronic equalization.

Since the first preferred embodiment is primarily intended for use in a radio communication application, the desired frequency response is 600 Hz to 3 kHz, ± 3 dB. As shown in FIGS. 6 and 7, the tubing length of 3.25 inches yields the response curve 600, which is relatively smooth or flat over the 600 Hz to 3 kHz range, and is therefore a good choice. Although without equalization the curve 600 is not within ± 3 dB of a target response curve, the response curve 600 does remain relatively flat down to 600 Hz, thus demonstrating the beneficial effects of the Helmholz resonance.

After the speaker driver, tubing inner diameter and tubing length have been chosen, any remaining deviations from the target response curve that are not within a specified tolerance can be corrected using electronic equalization and/or acoustic dampers. FIG. 8 shows an electronic circuit diagram of a passive equalizer circuit 800 for use with the first preferred embodiment, which equalizes an electronic signal provided to a speaker driver 810 from the communication device by attenuating excessive response peaks within the desired frequency band, while leaving the rest of the response relatively unaffected. FIG. 10 shows an actual equalization characteristic 1000 of the circuit 800, and FIG. 9 shows an ideal equalization characteristic 900. The ideal equalization characteristic is simply the inverse of the unequalized response shown in FIG. 7.

FIG. 11A shows the overall free field equivalent response 1100 of the system of the first preferred embodiment after equalization, and FIG. 11B shows the system response 1120 as measured at the tympanic membrane, in comparison with the 0° azimuth target response 1110.

As shown in FIG. 11A, the system has an SPL free field equivalent output that is greater than 110 dB at less than 3% THD. This is remarkable, especially in light of the fact that common wisdom in the art held that such a strong and clean output could not be achieved using an open canal configuration. To put this in perspective, communication sounds, e.g., speech, typically need to have an SPL that is greater than a background noise intensity by about 10 dB or more, in order for a user to reliably discern the communication sounds. Furthermore, an occlusive hearing aid or communication device typically attenuates ambient sound pressure levels by about 20 dB. This means that when a person such as a Secret Service agent wearing an occlusive communication device enters a crowded room that has an ambient noise level of about 95 dB SPL, his communication device will attenuate the noise to about a 75 dB SPL free field equivalent because it occludes his ear canal. Thus, his communication device needs to provide communication sounds that have an SPL free field equivalent of about 75 dB + 10 dB = 85 dB. In contrast, an open-canal device needs to provide communication sounds that have an SPL free field equivalent of about 95 dB + 10 dB = 105 dB.

Conventional wisdom held that available transducers could not provide such high output without also generating high levels of distortion. In accordance with the first preferred embodiment of the invention, Helmholz resonance and resonance due to tubing length augment the output at low and high frequencies, and the open-canal configuration allows the ear canal's natural resonance to augment midrange frequencies. Although the loss of the pinna effect can be further compensated for by driving the transducer harder at the higher frequencies corresponding to the pinna effect, doing so does not necessarily introduce distortion but instead further illustrates the elegance of the design of the first

preferred embodiment. For a given SPL, a transducer must move more air at low frequencies than at high frequencies. In other words, a member of the sound transducer for moving air, such as a diaphragm, must pass through a greater range of movement to produce a low frequency sound than for a high frequency sound of the same SPL. This in turn means that transducers typically can provide greater sound pressure levels, or sound intensities, at high frequencies than at low frequencies before introducing significant distortion. To use terms well known in the art, transducers typically have more "headroom" at higher frequencies. Thus, resonance is used to aid the transducer at lower frequencies where there is less headroom, and the transducer can be driven harder at higher frequencies, where it has more headroom, to compensate for the loss of the pinna effect. Thus, in the design of the first preferred embodiment the resonance is used to nicely balance limitations of conventional transducers.

Incidentally, an embodiment of the open-canal device of the present invention can be especially useful in open-canal hearing aids for users who need hearing augmentation only in portions of the sound spectrum. In such an open-canal hearing aid, high quality sound reproduction is provided by augmenting only those portions of the sound spectrum, while allowing the other portions of the sound spectrum to enter the ear naturally, through the open ear canal. Since the ear canal is open, the other portions of the sound spectrum are not attenuated and thus do not need to be restored or enhanced by the open-canal hearing aid. In contrast, closed-canal hearing aids attenuate all portions of the sound spectrum, and must therefore also amplify portions of the sound spectrum where the user does not otherwise need augmentation, to restore the attenuation caused by occluding the ear canal. Thus, open-canal hearing aids which can incorporate embodiments of the invention can be simpler in design and consume less power than closed-canal hearing aids, and do not distort the user's own voice.

In summary with respect to the first preferred embodiment, the Helmholz acoustic resonance effect is used to replace open-canal bass falloff, a tubing anti-

resonance is used to suppress the speaker driver's natural electroacoustic response peak, and equalization is used to replace the pinna effect and bring remaining portions of the response curve within a specified tolerance of the target response.

In the second preferred embodiment, an open-canal communication device such as an earpiece that is small in size, light in weight, high in comfort and provides a moderate output, is desirable for business applications. A small hearing aid receiver such as the Knowles ED-1932 can be used in the second preferred embodiment. As shown in FIG. 12, the ED-1932 has a strong, undamped +15 dB electroacoustic response peak that is tuned to occur near 2 kHz, to approximate the ear canal resonance frequency in a closed canal application (e.g., in a 2 cubic centimeter cavity). In a free field, this response peak occurs near 4 kHz.

As in the first preferred embodiment, a tubing diameter can be chosen and then the tubing length can be adjusted to provide a smoothest available free field frequency response, correcting for the 0° azimuth target response. The output requirement in the second preferred embodiment is modest, and simply requires an output that is greater than a free field equivalent of a 90 dB sound pressure level. Because the output requirement is modest and light weight and a high degree of comfort are desirable in the second preferred embodiment, a thin, light weight tubing is used, having, for example, an inner diameter of 0.023 inches. This small inner diameter (and corresponding small outer diameter, since the tubing wall can, for example, have a thickness on the order of 0.005 inches) confers the additional advantage that since the tubing is so slender, it can be nearly invisible and thus very discreet, especially when used as part of an open-canal communication device that is configured as an earpiece to fit behind a user's ear.

FIG. 13 shows free field equivalent response curves 1304, 1302, 1300, 1308 and 1306 for tubing lengths of 2.00 inches, 2.25 inches, 2.50 inches, 2.75 inches and 3.00 inches respectively. The Helmholz resonance peaks below 1 kHz shown in FIG. 13 are clearly seen, but the tubing resonances are less pronounced in comparison with the tubing resonances of the curves 600-608 shown in FIG. 6.

This is due to the smaller inner diameter of the tubing used in this embodiment, and the acoustic damping effect created by friction of moving air with the tubing walls. Also very evident in FIG. 13 is the electroacoustic peak of the ED-1932 near 4 kHz, for all the curves. FIG. 14 shows only the curve 1300 so that its shape can be easily seen.

In this design the speaker driver is powered using active circuitry, and thus an active electronic equalizer can easily be used. The full telecommunications bandwidth of 300 Hz to 3 kHz is required, and the tolerance can be selected to be within ± 4 dB. As in the first preferred embodiment, the ideal equalization characteristic can be obtained by inverting the response curve 1300. However, in view of practical considerations, instead of using an active equalization circuit with sharp or fine response deviations, a simpler and more gradual equalization characteristic 1500 can be used as shown in FIG. 15. The equalization characteristic 1500 can be easily produced in a simple, active filter circuit by conventional means. When the equalization characteristic 1500 is used with the earpiece system of the second preferred embodiment, the system has the overall free field equivalent response 1600 shown in FIG. 16A. FIG. 16B shows the system response 1620 as measured at the tympanic membrane, in comparison with the 0° azimuth target response 1610.

As shown in FIG. 16A, the design requirements for this system are satisfied; the output of 93 dB SPL is above the 90 dB requirement, and the bandwidth of 280 Hz to 4.6 kHz with ± 3.9 dB is better than required. Even the transducer's residual electroacoustic peak is not significant, and can be further reduced with acoustic dampers if desirable or necessary given different design requirements.

The equalization electronics and the speaker driver of the ED-1932 can be powered directly from the radio, cellular telephone, or other device with which the earpiece is being used, or can be powered by a separate battery. The battery can be

housed within the earpiece, or can be remotely located and connected to the earpiece via an electric cable.

In summary with respect the second preferred embodiment, a Helmholz resonator is used to correct for bass falloff, tubing with a relatively small inner diameter is used to acoustically damp the electroacoustic peak of the speaker driver, and high frequency portions of the electroacoustic peak together with moderate equalization are used to replace the pinna enhancement.

In the third preferred embodiment, a tiny, lower output, active delivery open-canal communication device is contemplated for use in consumer and small-office or home-office situations. In this embodiment, the speaker driver is placed at the end of the tube, in or near the entrance of the user's ear canal, as disclosed for example in copending applications ________________ (Attorney Docket Nos. 022577-353 and 022577-363, which are hereby incorporated by reference), without occluding the canal. The tube carries wires to the speaker driver, and the speaker driver has little or no tubing for acoustic loading. Since Helmholz resonance is not used in this embodiment, bass falloff is corrected by applying electronic equalization.

Alternatively, Helmholz resonance can be used. For example, in another embodiment similar to this one, Helmholz resonance and corresponding beneficial effects can be provided using an air volume within the transducer. The Helmholz resonance can be tuned, for example, by properly selecting a size and location of an aperture in the transducer housing, through which sound is provided to the user's ear. Absence of a tubing for acoustic loading will not prevent occurrence of the Helmholz resonance, in part because of "end effects" on either side of the aperture in the transducer housing. In summary, general principles of the Helmholz resonance effect are well known in the acoustic arts, and can be applied to produce the desired resonance effect.

In the third preferred embodiment, a transducer or speaker driver device such as the Knowles EP-7110 that is small enough to fit into the ear canal without

occluding it, and which has its own built in amplifier, is desirable. This also requires that the equalization be active, and that the electronic sound signal be equalized before it is amplified within the speaker driver device. Electrical power for the open-canal communication device of the third embodiment can be provided either from a device supplying the original signal (e.g., a radio, cellular telephone, cordless phone, tape player, CD player, etc.), or can be provided by a separate power source such as a battery. The separate power source can be housed, for example, in the connector body or in the earhook. In a wireless design, the separate power source is preferably located in the earhook.

The curve 1700 shown in FIG. 17 shows the non-equalized, free field equivalent response of the open-canal communication device of the third preferred embodiment. As shown in FIG. 17, the response is quite good above 1.5 kHz, extending to over 9kHz. Although the EP-7110 has a built-in amplifier and a variable reluctance motor that is driven with a voltage to produce additional bass, additional compensation for bass falloff below 1.5 kHz is desirable.

FIG. 18 is a circuit diagram of an active equalizer circuit 1800 incorporating a Gennum Corporation GS563 amplifier integrated circuit. The circuit 1800 is simple, small, and has very low power consumption. The circuit 1800 and the speaker driver 1810, shown as the EP-7110 device, can each be powered by a battery of the type commonly used in conventional hearing aids. The equalization circuit 1800 has the equalization characteristic 1900 shown in FIG. 19. When the equalization circuit 1800 having the equalization characteristic 1900 is used within the open-canal communication device of the third preferred embodiment, the device has the overall free field equivalent response 2000 shown in FIG. 20A. FIG. 20B shows the system response 2020 as measured at the tympanic membrane, in comparison with the 0° azimuth target response 2010.

In summary with respect to the third embodiment, bass falloff can be compensated for using simple equalization, and high frequency equalization can be used to replace the missing pinna enhancement. The effect of the electroacoustic

peak of the transducer can also be moderated by selecting a transducer that has built-in acoustic damping (as, for example, the "type-I" damping provided in the EP-7110).

In the fourth preferred embodiment, a low cost, passive open-canal communication device based on an earbud-type voice-coil speaker driver is contemplated for consumer applications where low device cost is important. In accordance with the objective of reducing device cost, in this embodiment small voice-coil speakers can be used, which are relatively inexpensive and readily available. In addition, to maximize simplicity and further minimize cost, a) the device design can be purely passive; b) electronic equalization can be omitted; c) requirements for tolerance on response curve flatness and for electroacoustic efficiency can be relaxed; and d) an open-back speaker driver configuration can be used.

Notwithstanding these simplifications, the open-canal communication device of the fourth preferred embodiment is capable of providing high-quality sound output. In particular, this device can provide very good bass response, even at high output levels, despite the open canal, a phenomenon that previous designers thought was impossible to achieve.

The speaker driver in the fourth preferred embodiment can be a voice-coil driver such as that used in the Sony MDR-WO8L Walkman™ stereo headphones. This driver uses a neodymium magnet for good efficiency, and is very small. The driver measures 13.5 millimeters in diameter and 3.8 millimeters in thickness, and can easily fit within a behind-the-ear (BTE) open-canal communication device. In the case of a voice-coil driver, the sound generated by the driver emanates from an open diaphragm instead of a small nozzle. Thus, the package for a voice-coil driver preferably includes a driver enclosure to capture the generated sound and direct it into a tube. Such a driver enclosure 2100 is shown in FIG. 21. The driver enclosure 2100 can, for example, be made of rigid plastic, or any other suitable material. The driver enclosure 2100 includes a sound output tube 2110, a rigid

plastic enclosure 2140, and a voice-coil speaker driver 2130. As can be seen in FIG. 21, the driver enclosure 2100 captures sound emanating from the front of the driver 2130 and directs it to the tubing 2110, while leaving the back of the driver 2130 open.

Length of the tubing 2110 is preferably selected to produce the Helmholz resonance at the lowest frequency of importance, which in this case is 60 Hz because the frequency response is specified to be flat from 60 Hz to 5 kHz, within ±5 dB. A diameter of the tubing can also selected to provide appropriate damping. For example, when a tubing having an inner diameter of 0.042 inches and a length of 1.5 inches is used with the voice-coil driver of the Sony MDR-WO8L Walkman™ stereo headphones in the open-canal communication device of the fourth preferred embodiment, the device has the overall free field equivalent response 2200 shown in FIG. 22A. FIG. 22B shows the system response 2220 as measured at the tympanic membrane, in comparison with the 0° azimuth target response 2210.

As shown in FIG. 22A, the open-canal communications device of the fourth embodiment exceeds the design objective of a flat response between 60 Hz and 5 kHz within ±5 dB. The device also achieves a 104 dB sound pressure level, average free field equivalent output while going down to 55 Hz. The effects of omitting equalization are also apparent in FIG. 22A. The excess output in the 1.5 kHz to 2.5 kHz region is partially due to the resonance of the ear canal. In addition, there is a falloff above 3 kHz which is due to lack of pinna enhancement. The tubing resonance, as clearly seen in FIG. 22A, was carefully placed at 5 kHz to make the overall response just meet the system requirements, but at the expense of a "dip" at 4 kHz. Acoustic dampers can be used in accordance with well known hearing aid methods to reduce the amplitude of the tubing-caused response ripples in the high frequencies (e.g., above 5 kHz).

In summary with respect to the fourth preferred embodiment, high output and good bass response are provided using a voice-coil driver in a low-cost design that omits electronic equalization.

FIGS. 23-27 show practical examples of earpieces which can incorporate embodiments of the invention. In particular, FIG. 23A shows an earpiece 2305 including a speaker driver 2314 that is contained within left and right side housings 2311, 2312 and which emits sound via a tube 2316. FIG. 23B shows the earpiece 2305 in its fully assembled form with an eartip 2318, and FIG. 23C shows the earpiece 2305 connected via a cable 2322 to a housing 2320 containing an electronic equalizer, which is in turn connected via a cable 2324 to a connector 2326.

FIGS. 24A-C show an earpiece 2410 with part of its housing removed to show a speaker driver 2414 and an electronics package 2416 located within the housing and connected to a sound delivery tube 2412. FIG. 24B shows the earpiece 2410 in its fully assembled form, and FIG. 24C shows the earpiece 2410 connected to a cable 2418 having a connector 2420.

FIGS. 25A-B show another earpiece design, wherein the earpiece 2510 has a speaker driver 2514 located at its tip and supported by a support tube 2518 which houses wires that provide electrical signals to the speaker driver 2514 from the cable 2516. A comfortable ear hook 2512 is also provided, which loops over a user's ear to comfortably suspend the speaker driver 2514 near or within the user's ear canal entrance. As shown in FIG. 25B, the earpiece 2510 is connected to a cable 2516 which has a connecter 2520 at its other end.

FIGS. 26 and 27 show another earpiece design 2600, which includes a voice-coil driver housing 2616 containing a voice-coil speaker driver 2620, a sound delivery tube 2614 for conveying sound from the voice-coil speaker driver 2620 to an eartip 2612. The eartip can be of the type disclosed in copending Application No. ______________, entitled "BTE Hearing Aid Tubing and Ear Canal Tips", Robert Fretz, et al., which is hereby incorporated by reference. The

earpiece 2600 also includes an earhook and cable housing 2618 which connects to a cable 2624. FIG. 27 is a cross-sectional view of the voice-coil driver housing 2616, along the lines 26-26. As shown in FIG. 27, the housing 2616 encloses a voice-coil speaker driver 2620, and has rear vent holes 2622 at the back of the driver 2620.

Embodiments of the invention can also incorporate the earpieces disclosed in copending applications entitled "Wired Open Ear Canal Earpiece" and "Wireless Open Ear Canal Earpiece" (Attorney Docket Nos. 022577-353 and 022577-363, respectively), which are hereby incorporated by reference.

According to another embodiment of the invention, a transducer having an electroacoustic resonance near 5 kHz can be used together with an equalizer configured to enhance only low frequency sounds. This combination will emit sound whose intensity is enhanced at low frequencies, is unchanged at middle frequencies corresponding to the canal resonance frequencies, and is enhanced at higher frequencies to emulate pinna function.

According to another embodiment of the invention, a transducer having a flat frequency response can be used with an equalizer configured to enhance higher frequency sounds to emulate pinna function and to enhance low frequency sounds, but provide no frequency enhancement to emulate or simulate canal resonance.

In accordance with the invention, electronic equalizers can be configured in different ways and matched to transducers having different response characteristics, so that they together emit sound that is appropriately enhanced at low frequencies and high frequencies as described above.

In addition, as for example described above with respect to the first, second and third embodiments, acoustic properties of tubes used to deliver sound can be used in addition to, or instead of, an equalizer and/or the nonlinear response characteristic of the transducer to achieve the desired sound profile in the user's ear canal. The tube can be configured according to well known principles governing acoustic effects of tube design, and can additionally or alternatively be

variously provided with stubs, acoustic dampers, and vents to tune the acoustic behavior of the tube.

Various acoustic dampers and methods well known in the art can be used. FIG. 28 shows, for example, an acoustic damper 2800 that can inserted in the tube. The Knowles company makes a series of such acoustic dampers, which are filled internally with materials selected to provide a specified acoustic impedance. An acoustic damper can be configured with outer dimensions such as a 1 millimeter outer diameter and a 2 millimeter length, so that it can fit inside a standard hearing aid tube having a 1 millimeter inner diameter.

FIG. 29 is a cross-sectional view of a section of acoustic tubing 2900 provided with a vent 2910 and a stub 2920. Various forms of vents and stubs can be used, in accordance with general principles and designs well known in the acoustic arts.

In accordance with another aspect of the invention, where electroacoustic resonance and acoustic tuning are efficient and effective ways of generating and altering sound, power consumption can be minimized and device simplicity can be maximized. In particular, a transducer and a tube can be configured to together provide amplification that is close to the desired frequency response profile but exceeds the profile in particular regions. An electronic frequency equalizer can be used with the transducer and the tube, to selectively reduce the electronic input signal provided to the transducer in the particular regions so that output of the tube matches the desired profile within predetermined tolerances. An advantage of this arrangement is that since the electronic frequency equalizer only attenuates portions of the input signal and does not significantly amplify the signal, it can be implemented as a passive electronic filter which does not require an external power source to operate, and which can be simpler and cheaper than an active electronic equalizer.

Those skilled in the art will also realize that embodiments of the invention can be used to provide monophonic or stereophonic sound, can use open or closed-

back transducers, and can be used in conjunction with a microphone to provide two-way communications, or can be used without a microphone as a simple, high quality earphone system providing one-way communication.

Those skilled in the art will further recognize that signals within embodiments of the invention can be implemented in various forms. For example, the signals can be electrical. The signals can also be light signals, transmitted for example through optical fibers. The signals can also be analog and/or digital.

It will be appreciated by those skilled in the art that the present invention can be embodied in other specific forms without departing from the spirit or essential characteristics thereof, and that the invention is not limited to the specific embodiments described herein. The presently disclosed embodiments are therefore considered in all respects to be illustrative and not restrictive. The scope of the invention is indicated by the appended claims rather than the foregoing description, and all changes that come within the meaning and range and equivalents thereof are intended to be embraced therein.

Claims:

1. An open ear canal communications device, comprising:

a sound processor for receiving a first signal representing a first sound, and altering the first signal to generate a second signal; and

a sound transducer for emitting a second sound near an entrance of a user's open ear canal in response to the second signal; wherein

differences between the second sound emitted by the transducer and the first sound represented by the first signal are greater at frequencies below and above a resonance of the ear canal than at frequencies within the resonance of the ear canal.

2. The device of claim 1, wherein the first signal is electronic.

3. The device of claim 1, wherein the first signal is digital.

4. The device of claim 1, wherein the first signal is analog.

5. The device of claim 1, further comprising a tube connected at one end to the transducer for conveying the second sound emitted by the transducer, wherein the device is configured to position the other end of the tube at an opening of the ear canal so that the ear canal is at least partially open for directly receiving ambient sounds.

6. The device of claim 1, wherein the sound transducer amplifies frequencies above the resonance of the ear canal.

7. The device of claim 1, wherein differences between the second sound and the first sound at frequencies above the resonance of the ear canal substantially correspond to a high frequency amplification provided by the acoustic properties of the user's outer ear.

8. The device of claim 1, wherein the sound transducer amplifies frequencies below the resonance of the ear canal.

9. The device of claim 1, wherein the sound transducer amplifies a set of frequencies and the sound processor attenuates selected ones of the set of frequencies.

10. The device of claim 1, wherein differences between the second sound emitted by the transducer and the first sound represented by the first electronic signal are generated by at least one of the sound processor, electromechanical components of the transducer, and acoustic components of the transducer.

11. The device of claim 10, wherein the acoustic components of the transducer include an ear canal tube that emits the second sound in an entrance of the user's ear canal.

12. The device of claim 11, wherein the acoustic components further include at least one of:

a) at least one vent in the tube;

b) at least one stub in the tube; and

c) at least one acoustic damper.

13. An open ear canal communications device, comprising:

a sound processor for receiving a first electronic signal representing sound, and altering the first electronic signal to generate a second electronic signal; and

a sound transducer for emitting sound in a user's open ear canal in response to the second electronic signal; wherein

the communications device enhances an intensity of the emitted sound at low frequencies to compensate for a loss of sound energy into an ambient space surrounding the user's ear, reproduces sound intensities in ear canal resonance frequency bands with a flat overall response, and enhances an intensity of the emitted sound at high frequencies to emulate the acoustic properties of the user's outer ear.

14. The communications device of claim 13, wherein the intensity enhancement of the emitted sound at low frequencies has a slope of about 12 decibels per frequency octave.

15. An open ear canal communications device, comprising:

a sound transducer unit for receiving a first signal representing a first sound, and emitting a second sound based on the first signal; and

a tube connected at one end to the sound transducer unit for receiving the second sound and emitting a third sound at the other end that corresponds to the second sound; wherein

the third sound, after being provided at an entrance of a user's open ear canal and traveling through the ear canal to the user's tympanic membrane, has a profile at the tympanic membrane that is similar within predetermined tolerances to a profile that the first sound would have at the tympanic membrane after being emitted in free field, being gathered by the user's outer ear, and traveling through the ear canal to the tympanic membrane.

16. The device of claim 15, wherein the predetermined tolerances include a predetermined sound intensity variation over a predetermined frequency range.

17. The device of claim 16, wherein the predetermined intensity variation is less than ±5 Decibels.

18. The device of claim 16, wherein the lower bound of the predetermined frequency range is less than 600 Hertz.

19.The device of claim 16, wherein the upper bound of the predetermined frequency range is greater than 3000 Hertz.

20. The device of claim 15, wherein a volume of air surrounded by the tube cooperates with a volume of air within the sound transducer to produce a Helmholz resonance that amplifies the second sound at frequencies below an ear canal resonance to produce the third sound.

21. The device of claim 15, wherein an inner diameter of the tube operates to damp the second sound at at least one of a) frequencies that are near the ear canal resonance and b) frequencies that are above the ear canal resonance.

22. The device of claim 15, wherein a length of the tube generates at least one resonance peak above the ear canal resonance.

23. The device of claim 15, wherein a length of the tube generates at least one resonance valley near the ear canal resonance.

24. The device of claim 15, wherein the sound transducer unit has an electroacoustic peak above the ear canal resonance.

25. The device of claim 15, further including at least one of:

a) at least one vent in the tube;

b) at least one stub in the tube; and

c) at least one acoustic damper.

26. The device of claim 15, wherein:

the sound transducer unit comprises an equalizer and a sound transducer;

the equalizer receives and alters the first signal representing the first sound to produce a second signal, wherein the second signal represents the first sound with amplification at at least one of a) frequencies below an ear canal resonance and b) frequencies above an ear canal resonance; and

the sound transducer emits the second sound based on the second signal.

27. A method for reproducing a sound at a user's tympanic membrane that corresponds to an open air sound, comprising the steps of:

receiving a signal representing the open air sound;

adjusting the signal at frequencies below ear canal resonant frequencies to compensate for a loss of sound energy into a free field around the user that increases with wavelength;

adjusting the signal at frequencies above ear canal resonant frequencies to compensate for absence of high frequency amplification performed by the user's outer ear;

maintaining the signal at ear canal resonant frequencies;

generating a sound based on the adjusted and maintained portions of the signal; and

providing the generated sound near an entrance of the user's unoccluded ear canal.

28. The method of claim 27, further comprising the step of adjusting the signal to compensate for response characteristics of a transducer used to generate the sound.

29. A method for reproducing a sound at a user's tympanic membrane that corresponds to an open air sound, comprising the steps of:

receiving a signal representing the open air sound;

generating a sound based on the signal;

adjusting the sound at frequencies below ear canal resonant frequencies to compensate for a loss of sound energy into a free field around the user that increases with wavelength; and

providing the generated sound near an entrance of the user's unoccluded ear canal.

30. The method of claim 29, wherein the step of adjusting the sound at frequencies below ear canal resonance frequencies is performed using a Helmholz resonator.

31. The method of claim 29, further comprising the step of adjusting the sound at frequencies above ear canal resonance frequencies to compensate for absence of high frequency amplification performed by the user's outer ear, using a resonance substantially determined by a length of a tubing that emits the adjusted sound near the entrance of the user's ear canal.

32. The method of claim 29, wherein the step of adjusting the sound at frequencies below ear canal resonant frequencies to compensate for the loss of sound energy into the free field around the user is performed using a resonance of a tubing that emits the adjusted sound near the entrance of the user's ear canal, where the resonance of the tubing is substantially determined by a length of the tubing.

33. The method of claim 32, wherein the step of adjusting the sound at frequencies below ear canal resonant frequencies further includes smoothing the

tubing resonance using a damping effect substantially determined by an inner diameter of the tubing.

34. The method of claim 32, wherein the tubing resonance is tuned using at least one of:

a) at least one vent in the tube;

b) at least one stub in the tube; and

c) at least one acoustic damper.

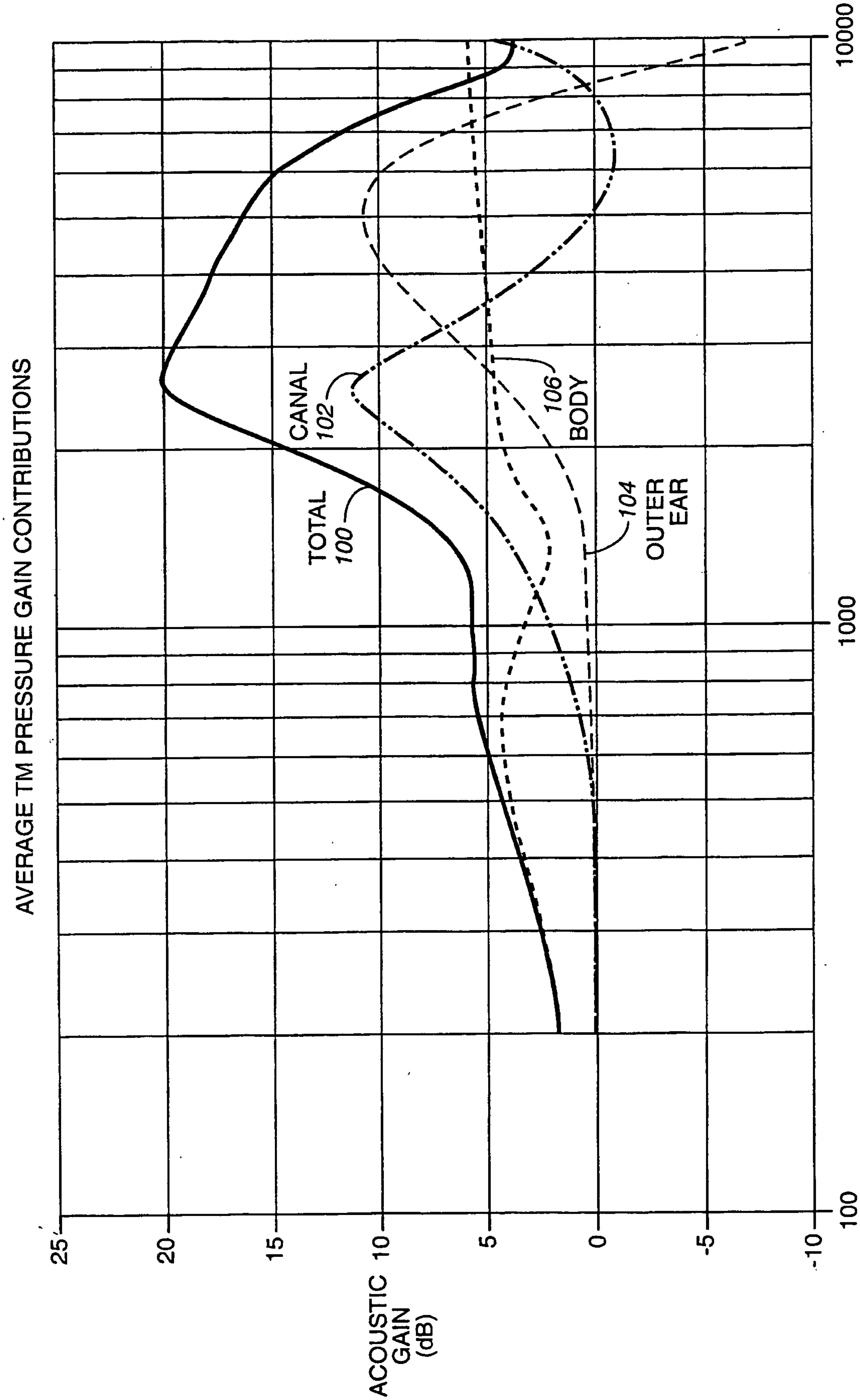

AVERAGE TM PRESSURE GAIN CONTRIBUTIONS
ACOUSTIC GAIN (dB)
25
20
15
10
5
0
-5
-10
100
1000
10000
FREQ (Hz)
TOTAL 100
CANAL 102
104 OUTER EAR
106 BODY

FIG._1

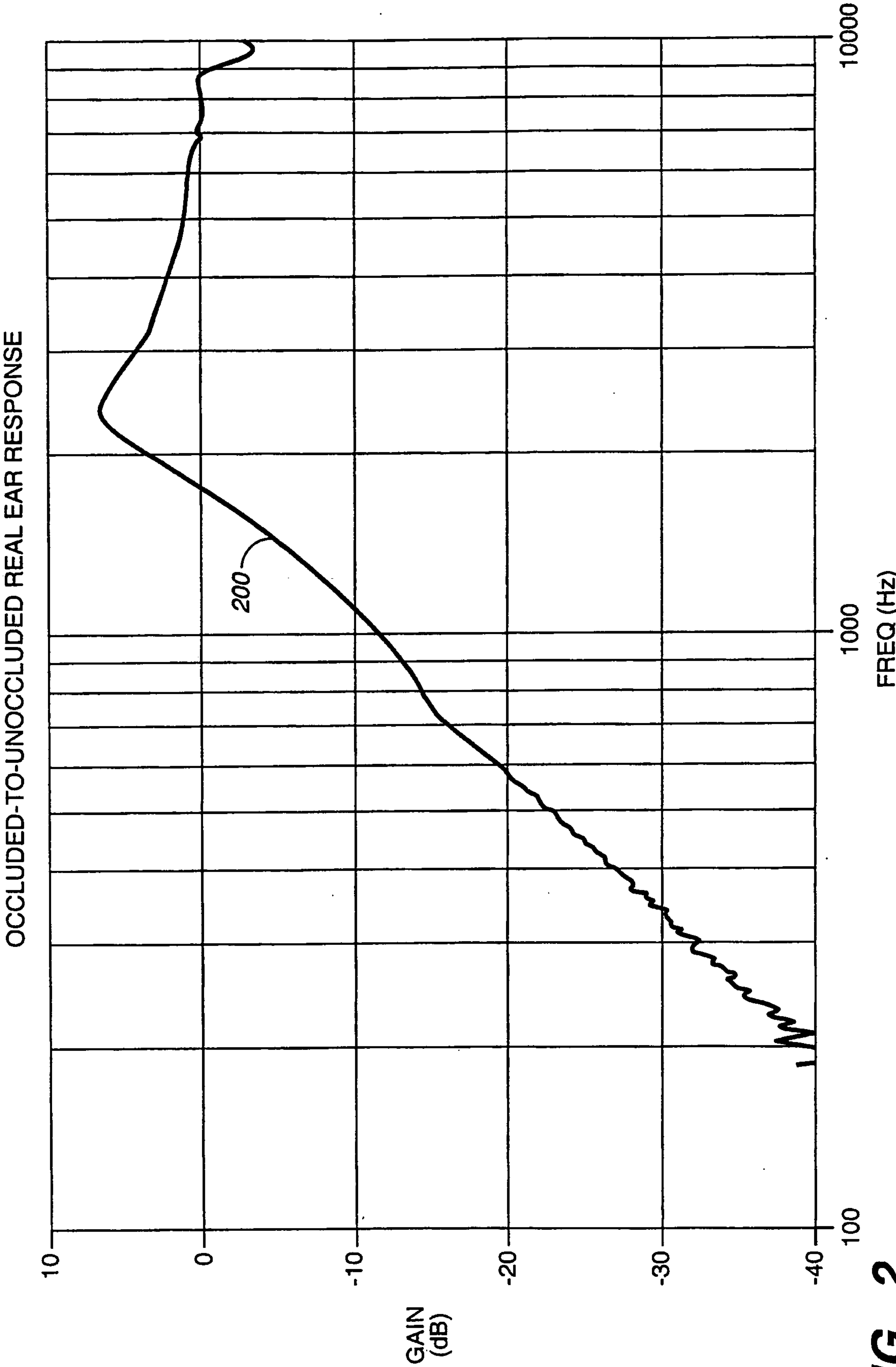

OCCLUDED-TO-UNOCCLUDED REAL EAR RESPONSE
GAIN (dB)
10
0
-10
-20
-30
-40
100
1000
10000
FREQ (Hz)
200

FIG._2

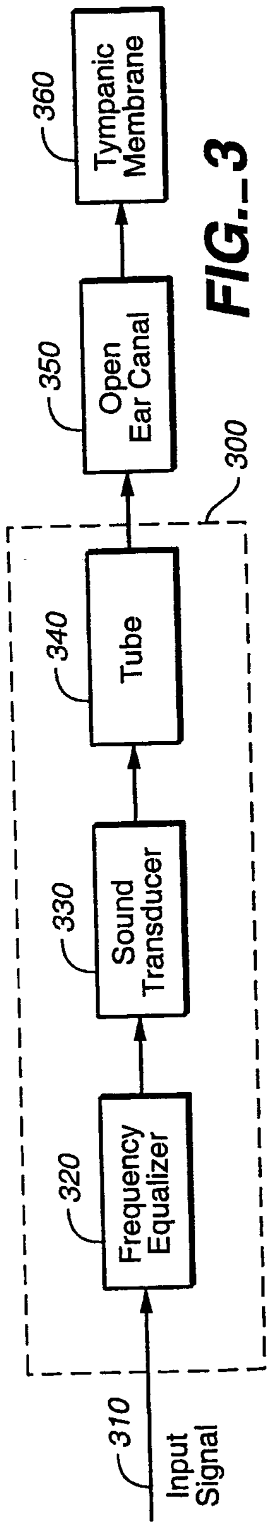

310
Input Signal
300
320
Frequency Equalizer
330
Sound Transducer
340
Tube
350
Open Ear Canal
360
Tympanic Membrane

FIG._3

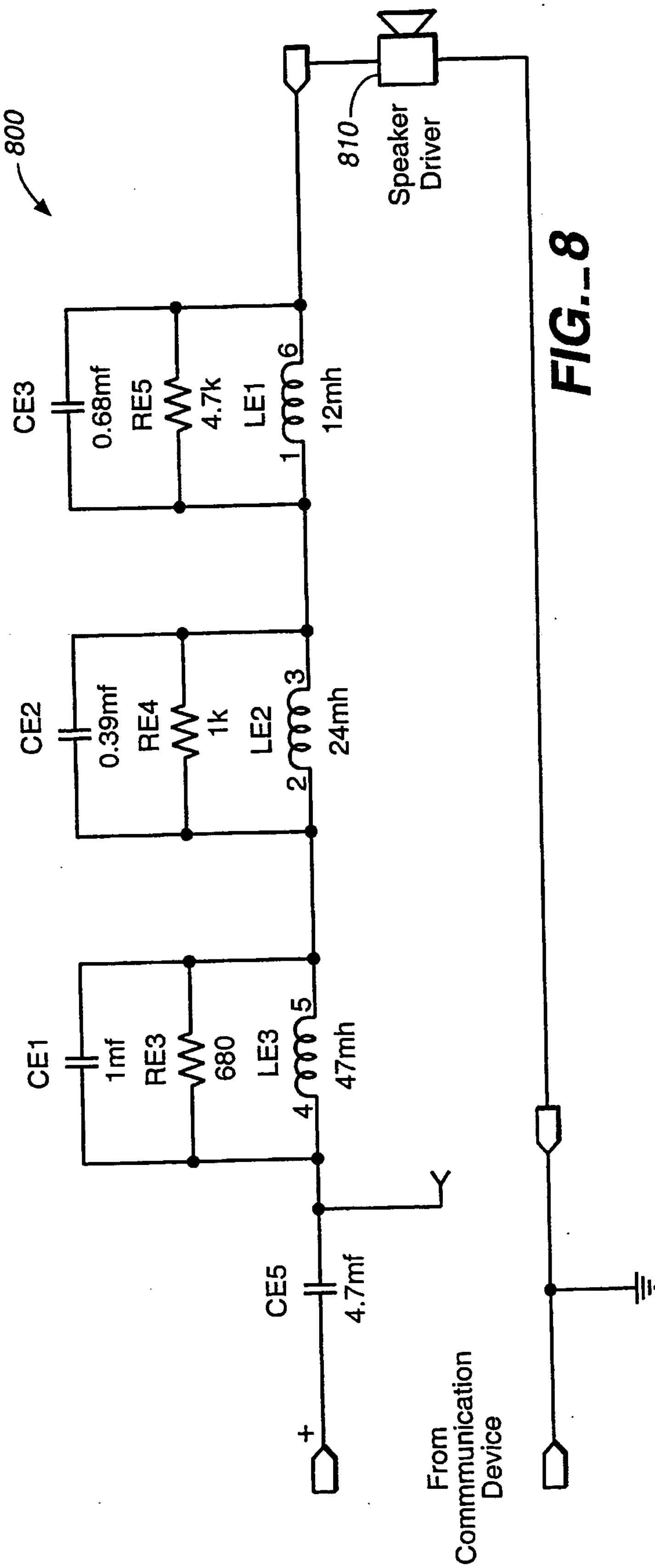

800
+
CE5
4.7mf
CE1
1mf
RE3
680
LE3
4
5
47mh
CE2
0.39mf
RE4
1k
LE2
2
3
24mh
CE3
0.68mf
RE5
4.7k
LE1
1
6
12mh
810
Speaker Driver
From Commmunication Device

FIG._8

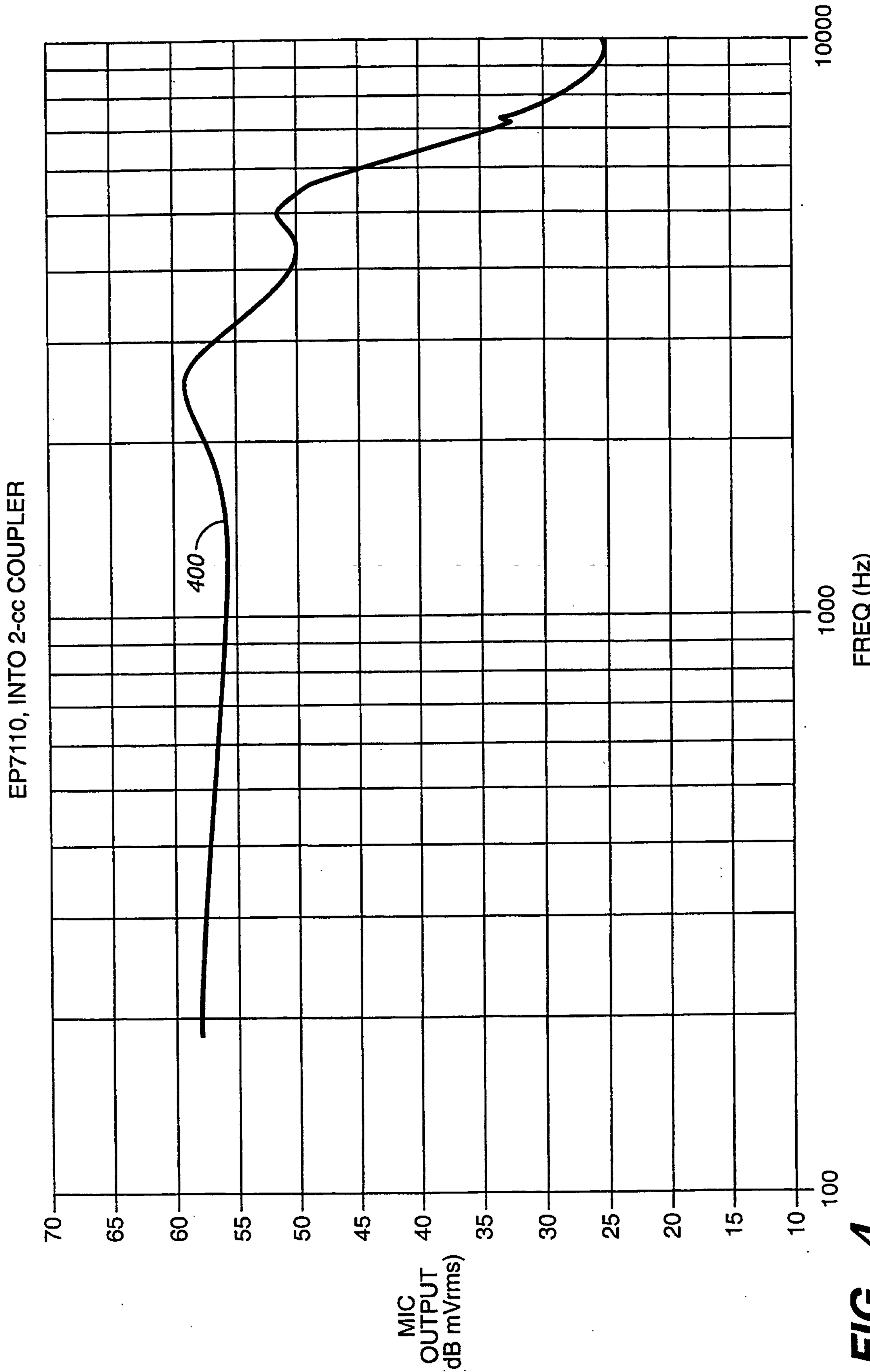

EP7110, INTO 2-cc COUPLER
400
MIC OUTPUT dB mVrms)
70
65
60
55
50
45
40
35
30
25
20
15
10
100
1000
10000
FREQ (Hz)

FIG._4

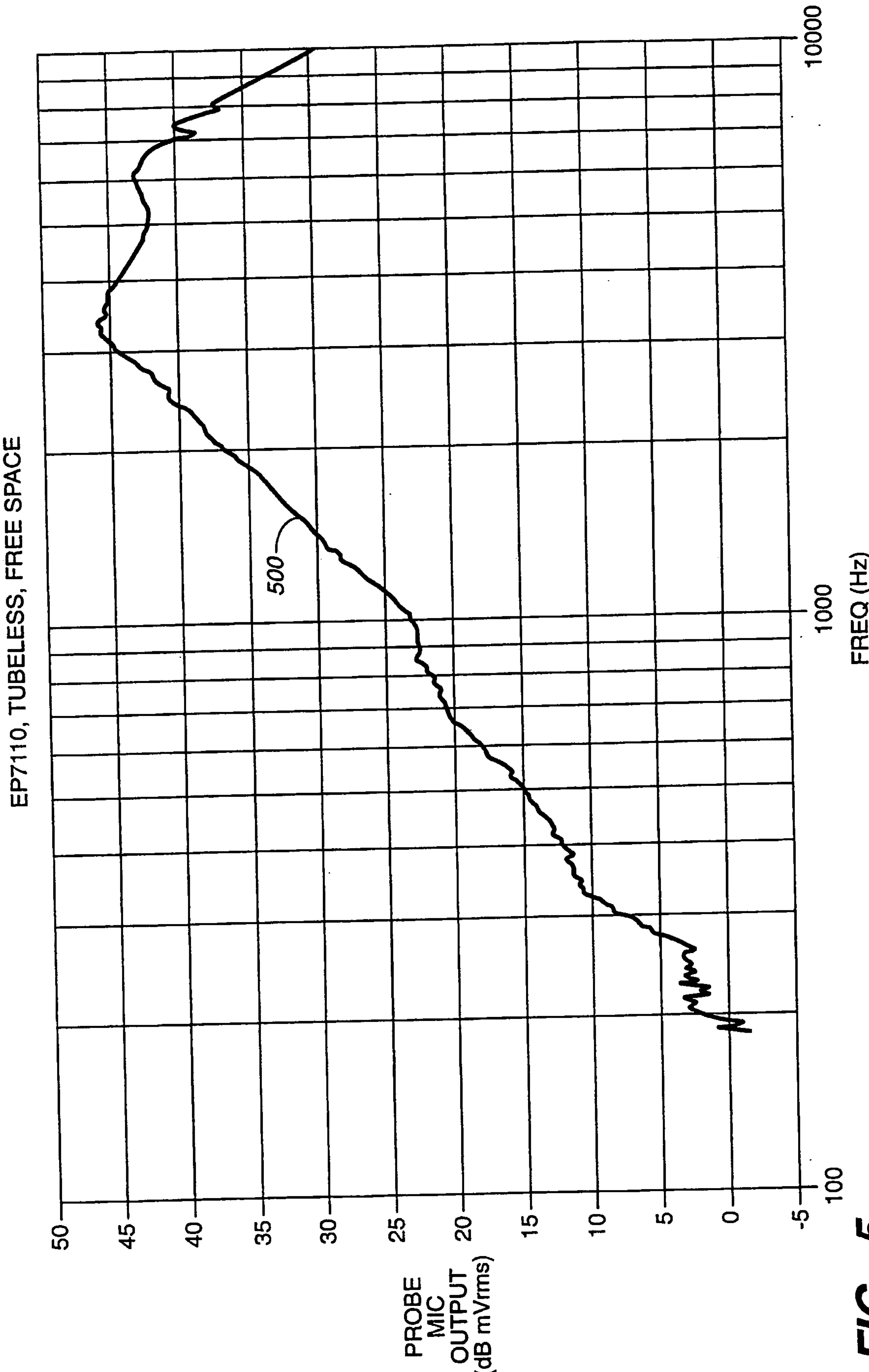

EP7110, TUBELESS, FREE SPACE
PROBE MIC OUTPUT (dB mVrms)
50
45
40
35
30
25
20
15
10
5
0
-5
100
1000
10000
FREQ (Hz)
500

FIG._5

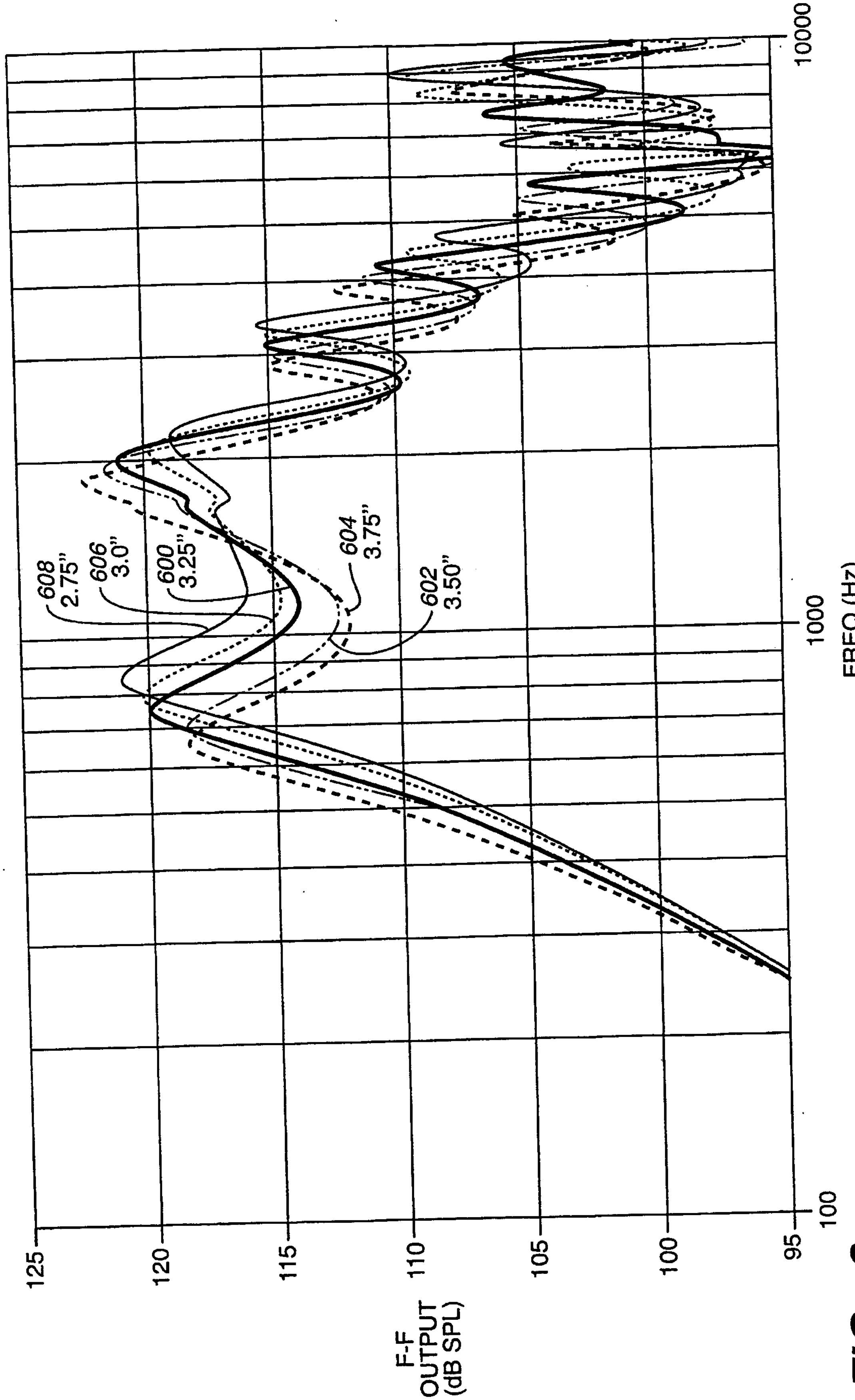

F-F
OUTPUT
(dB SPL)
125
120
115
110
105
100
95
100
1000
10000
FREQ (Hz)
608
2.75"
606
3.0"
600
3.25"
604
3.75"
602
3.50"

FIG._6

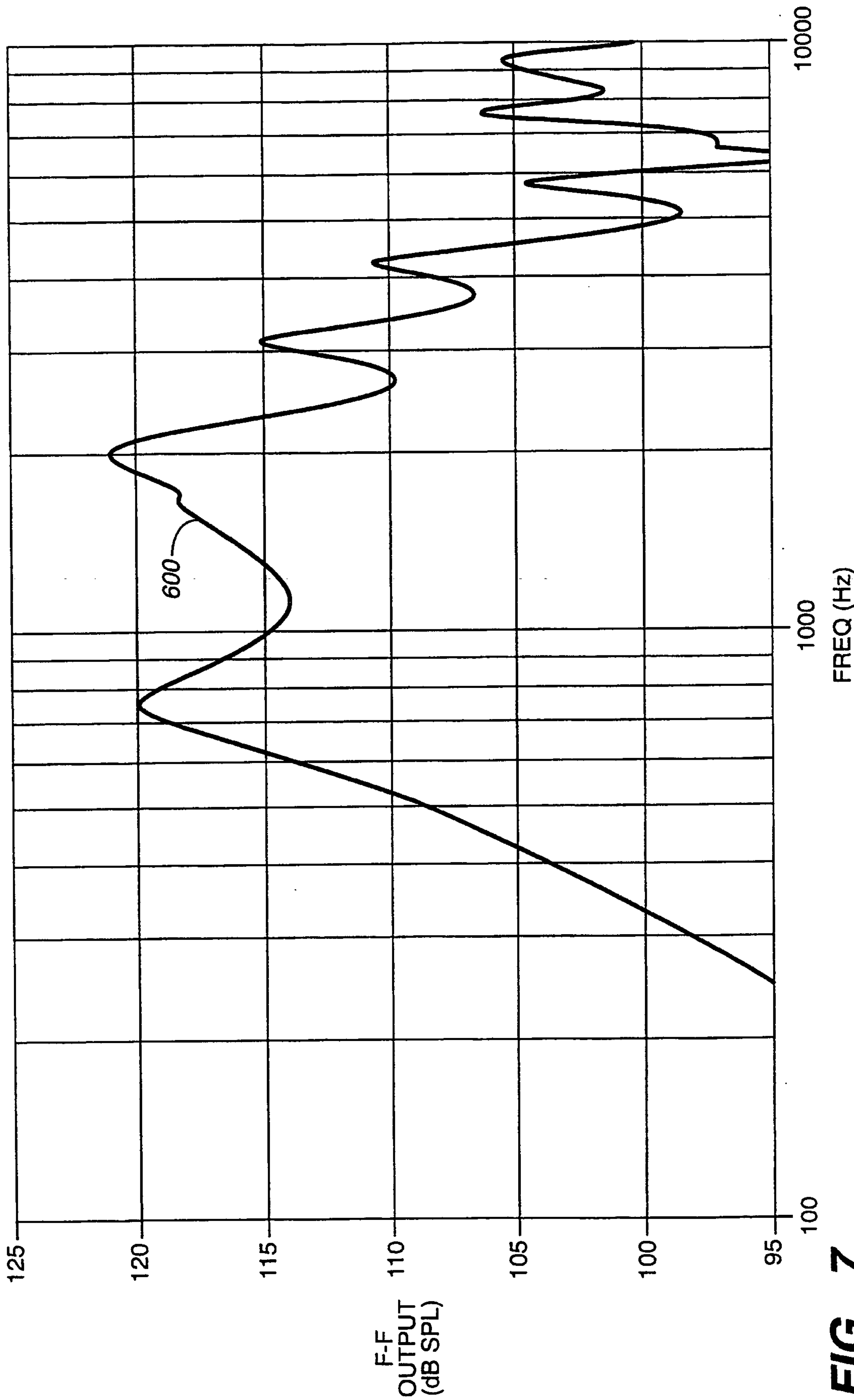

125
120
115
110
105
100
95
F-F
OUTPUT
(dB SPL)
100
1000
10000
FREQ (Hz)
600

FIG._7

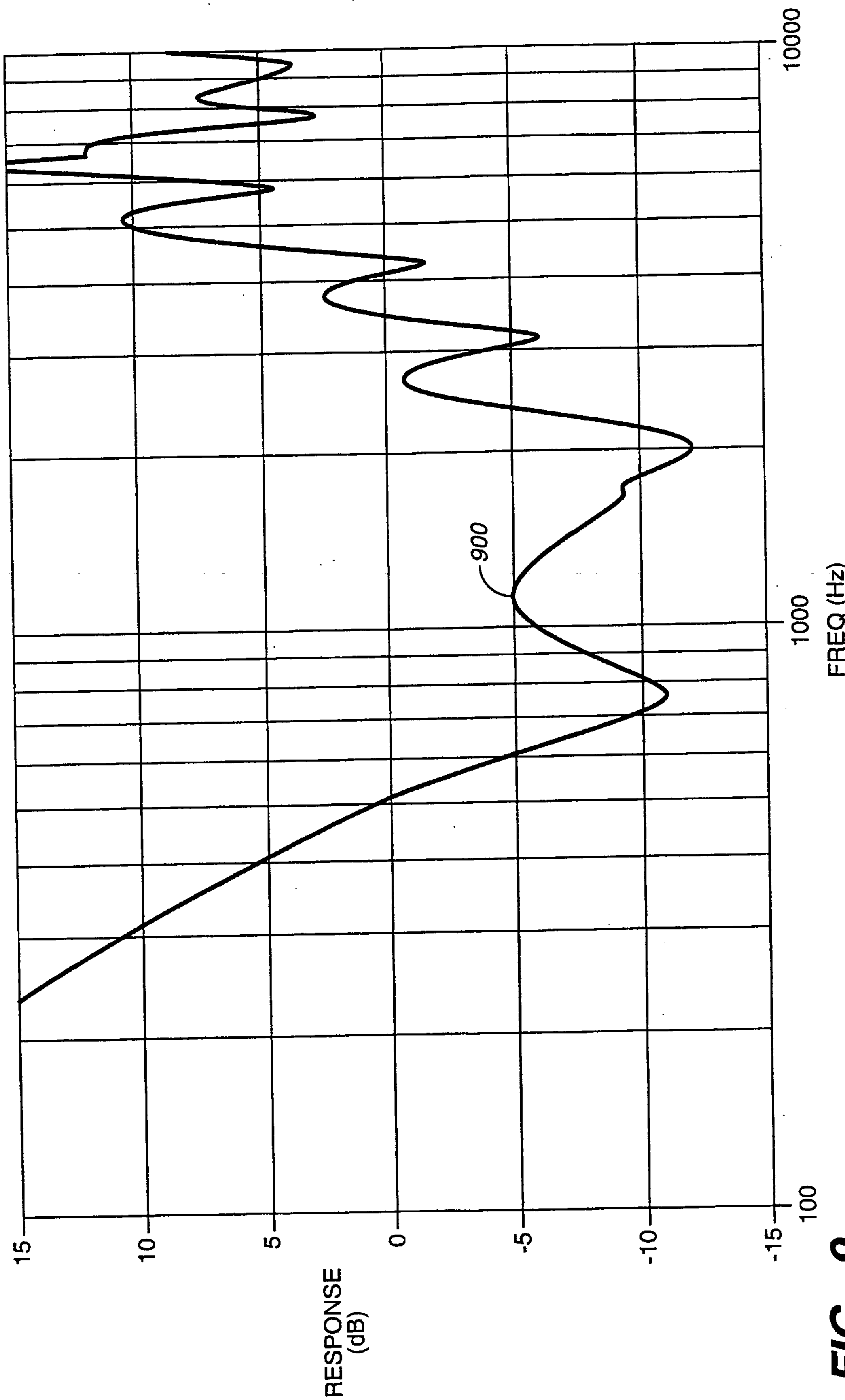


FIG._9

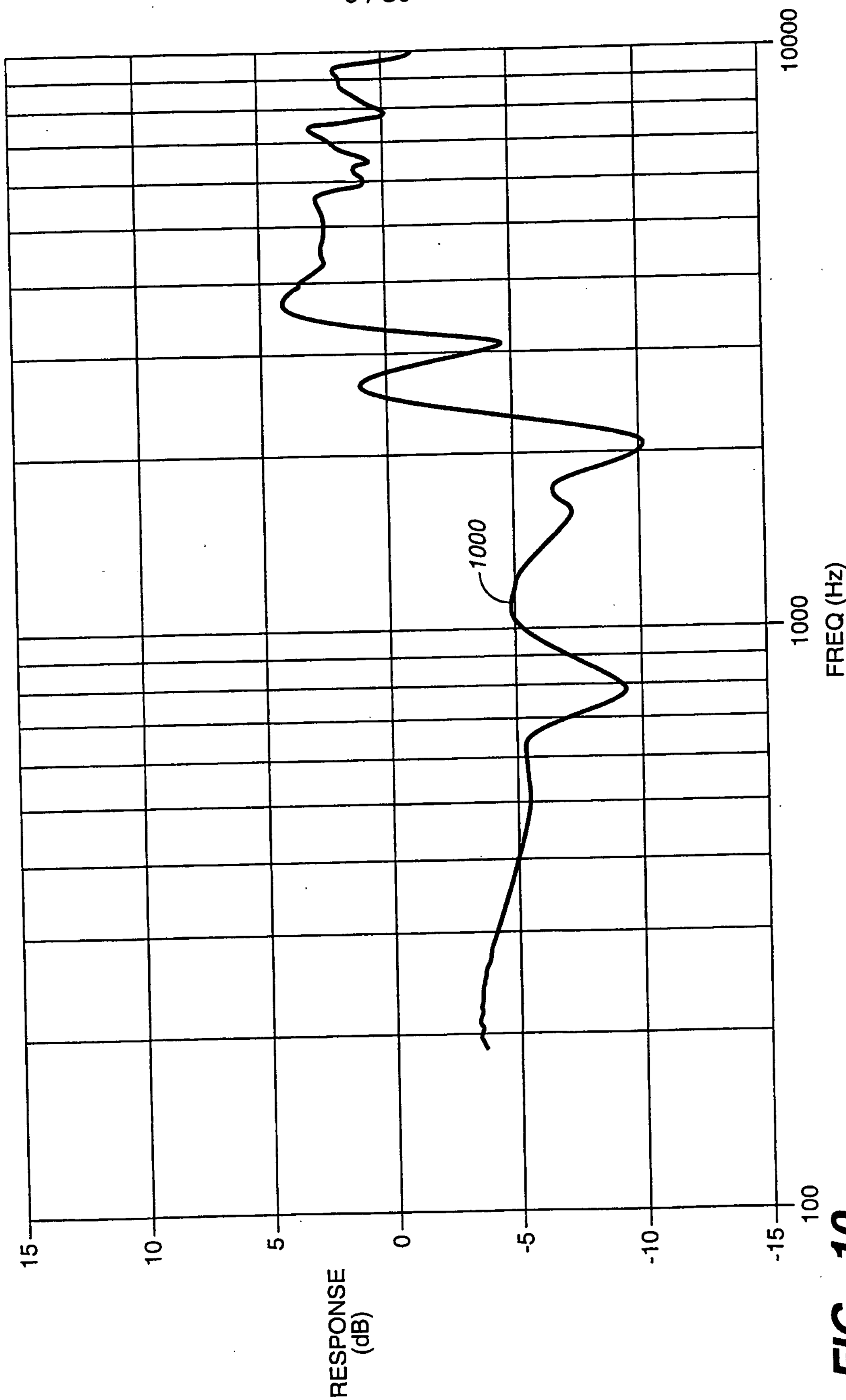


FIG._10

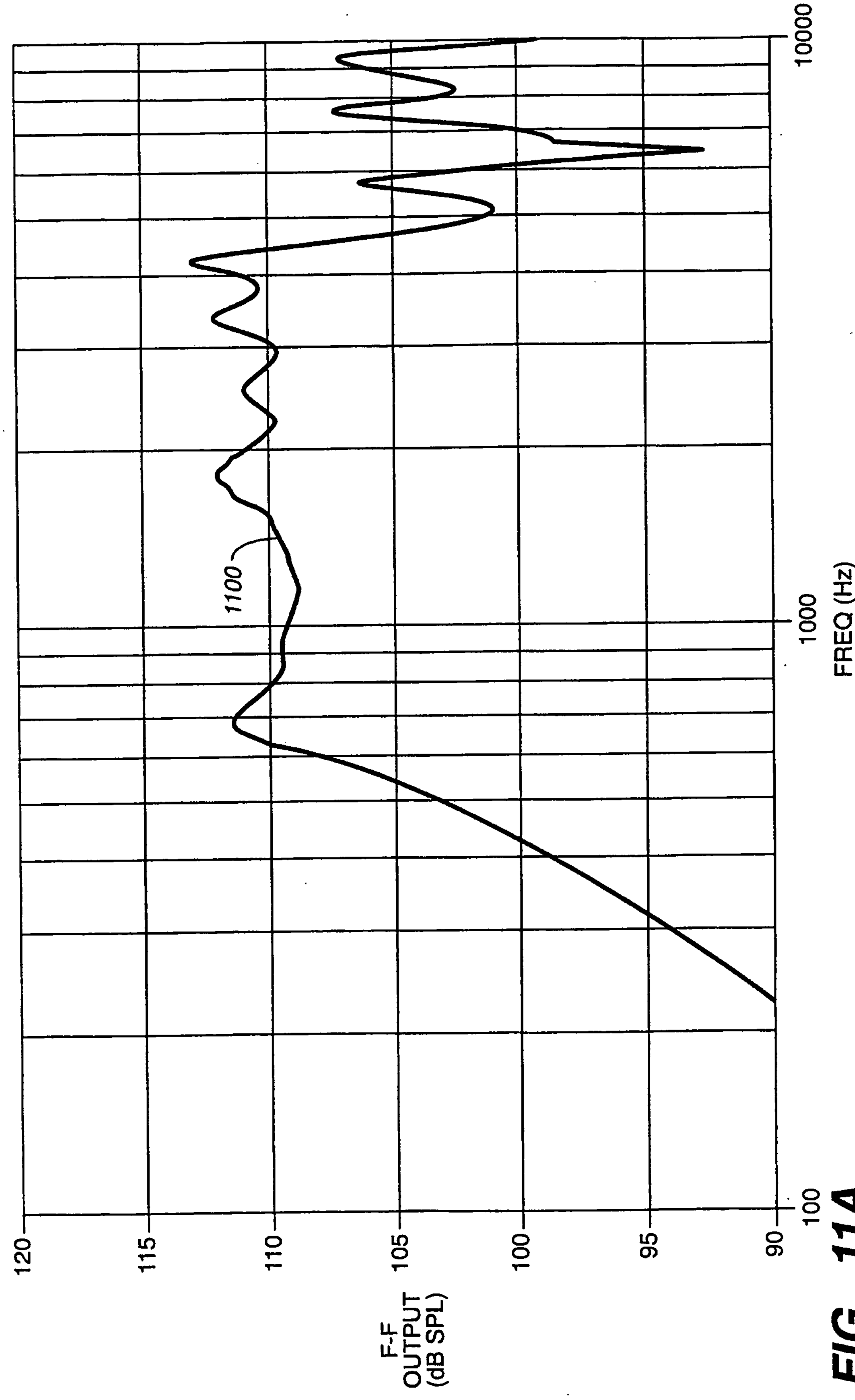
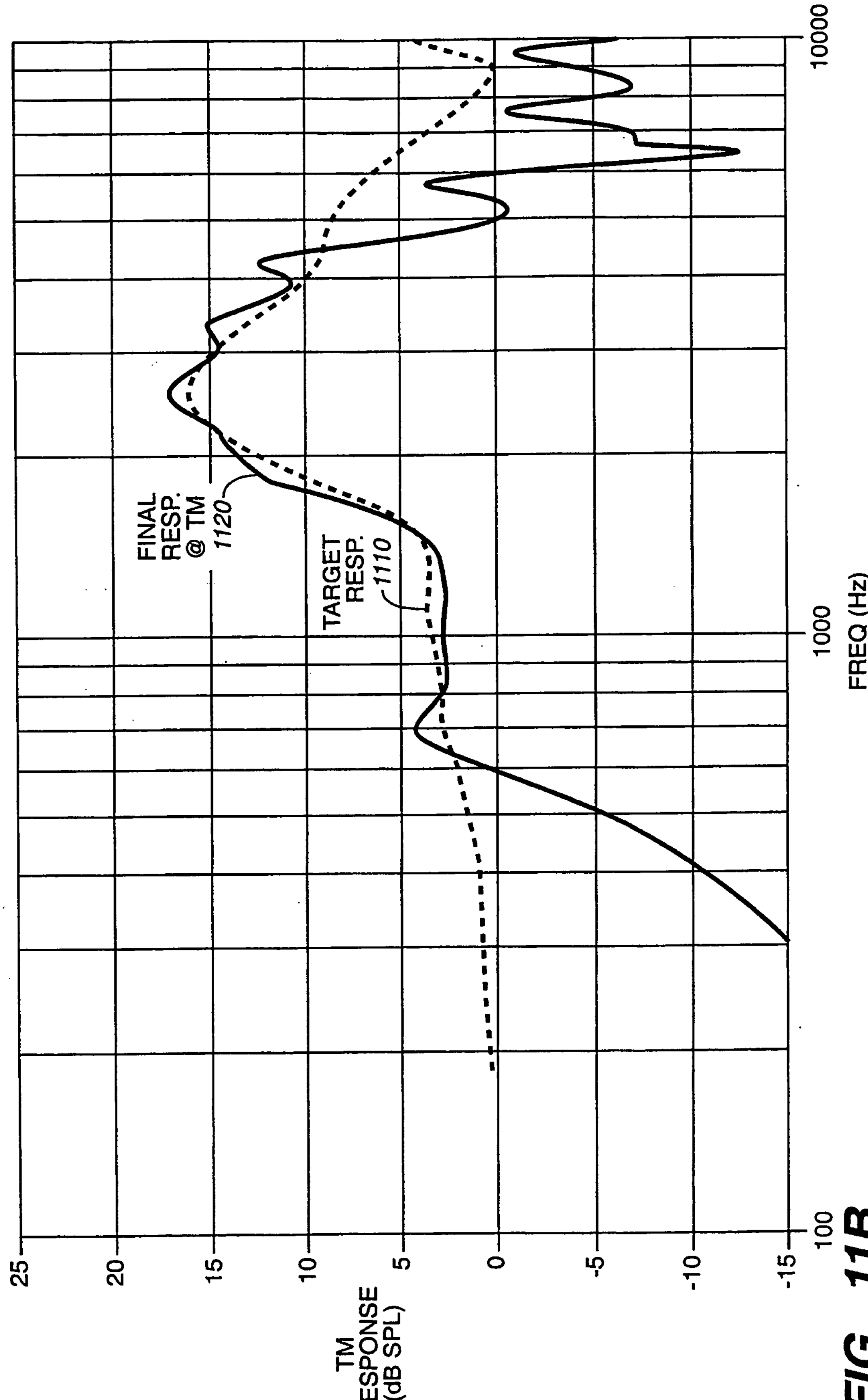
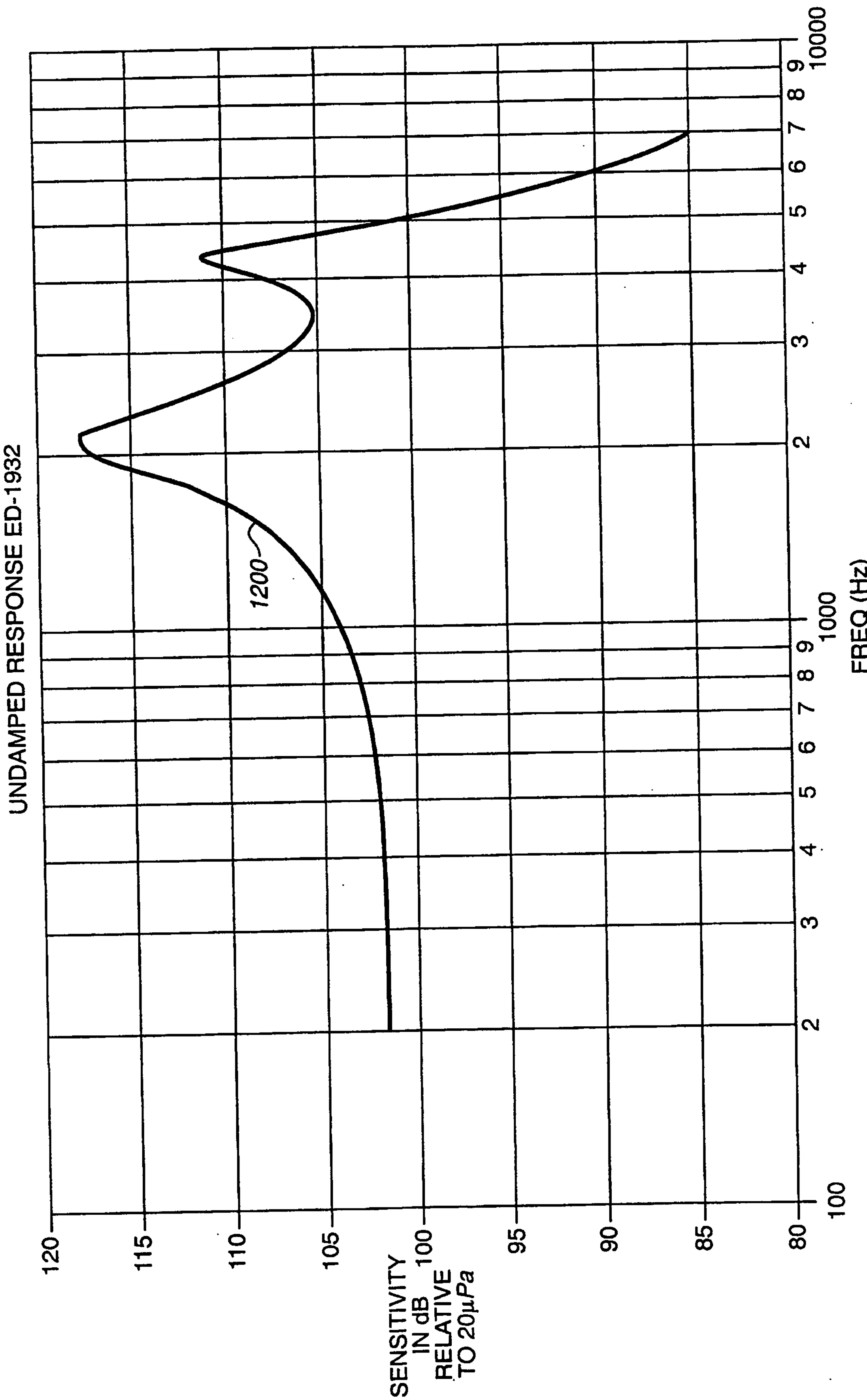

1100
F-F
OUTPUT
(dB SPL)
120
115
110
105
100
95
90
100
1000
10000
FREQ (Hz)

FIG._11A



TM RESPONSE (dB SPL)
25
20
15
10
5
0
-5
-10
-15
100
1000
10000
FREQ (Hz)
FINAL RESP. @ TM
1120
TARGET RESP.
1110

FIG._11B



RESPONSE MEASURED USING 10mm X 1mm TUBE INTO 2cm^3 CAVITY.

FIG._12

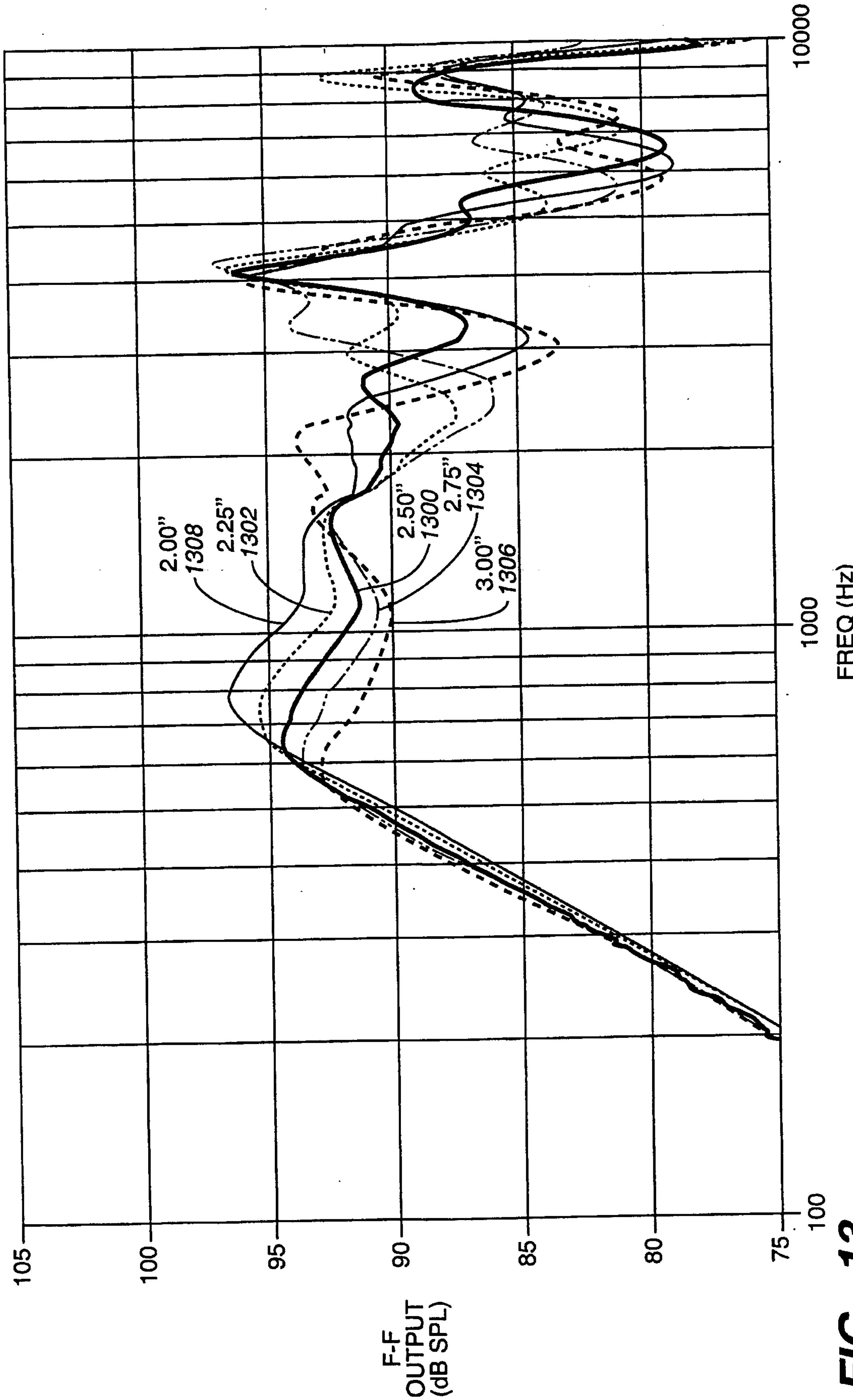

F-F
OUTPUT
(dB SPL)
105
100
95
90
85
80
75
100
1000
10000
FREQ (Hz)
2.00"
1308
2.25"
1302
2.50"
1300
2.75"
1304
3.00"
1306

FIG._13

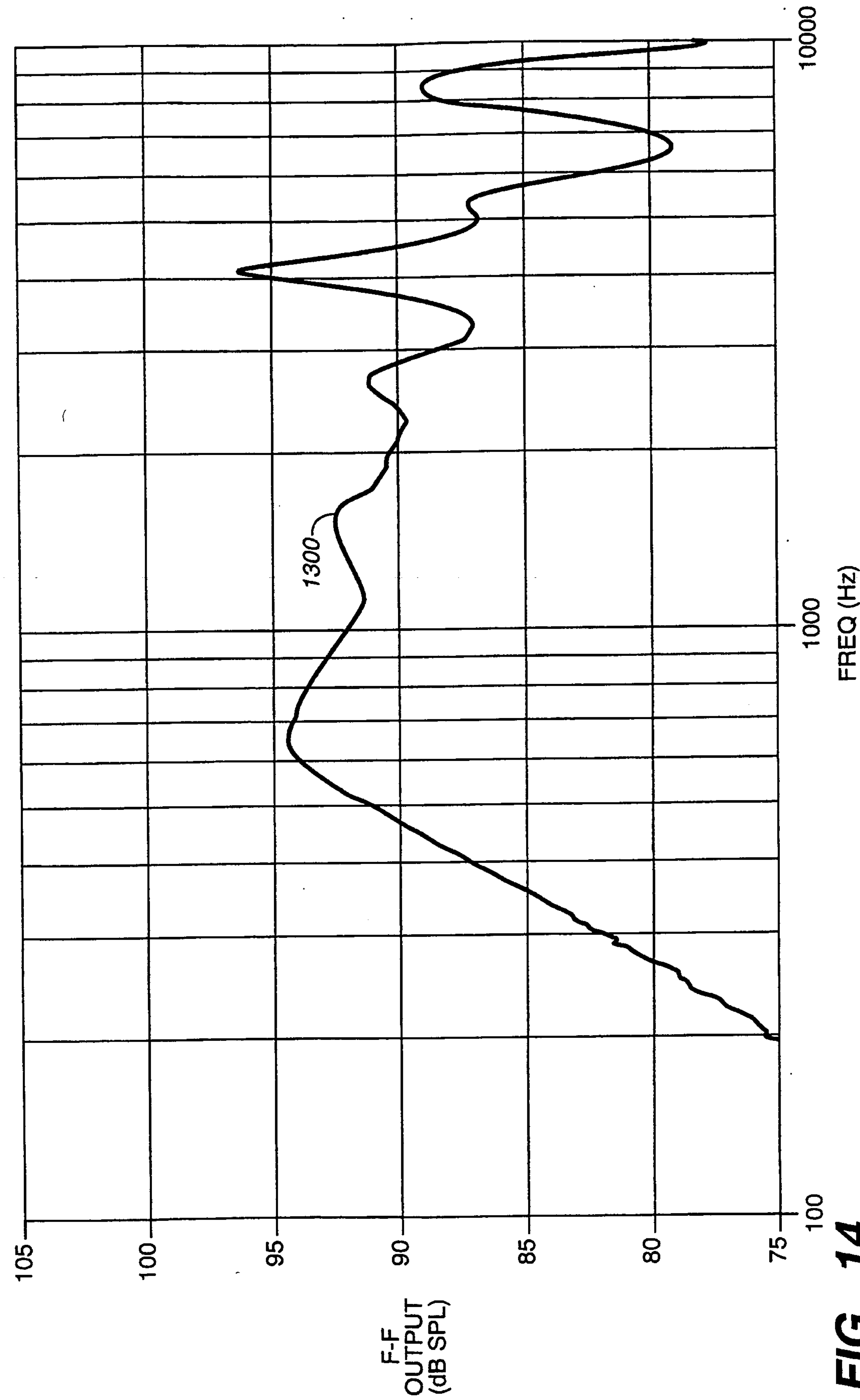

10000
1000
100
FREQ (Hz)
105
100
95
90
85
80
75
F-F
OUTPUT
(dB SPL)
1300

FIG._14

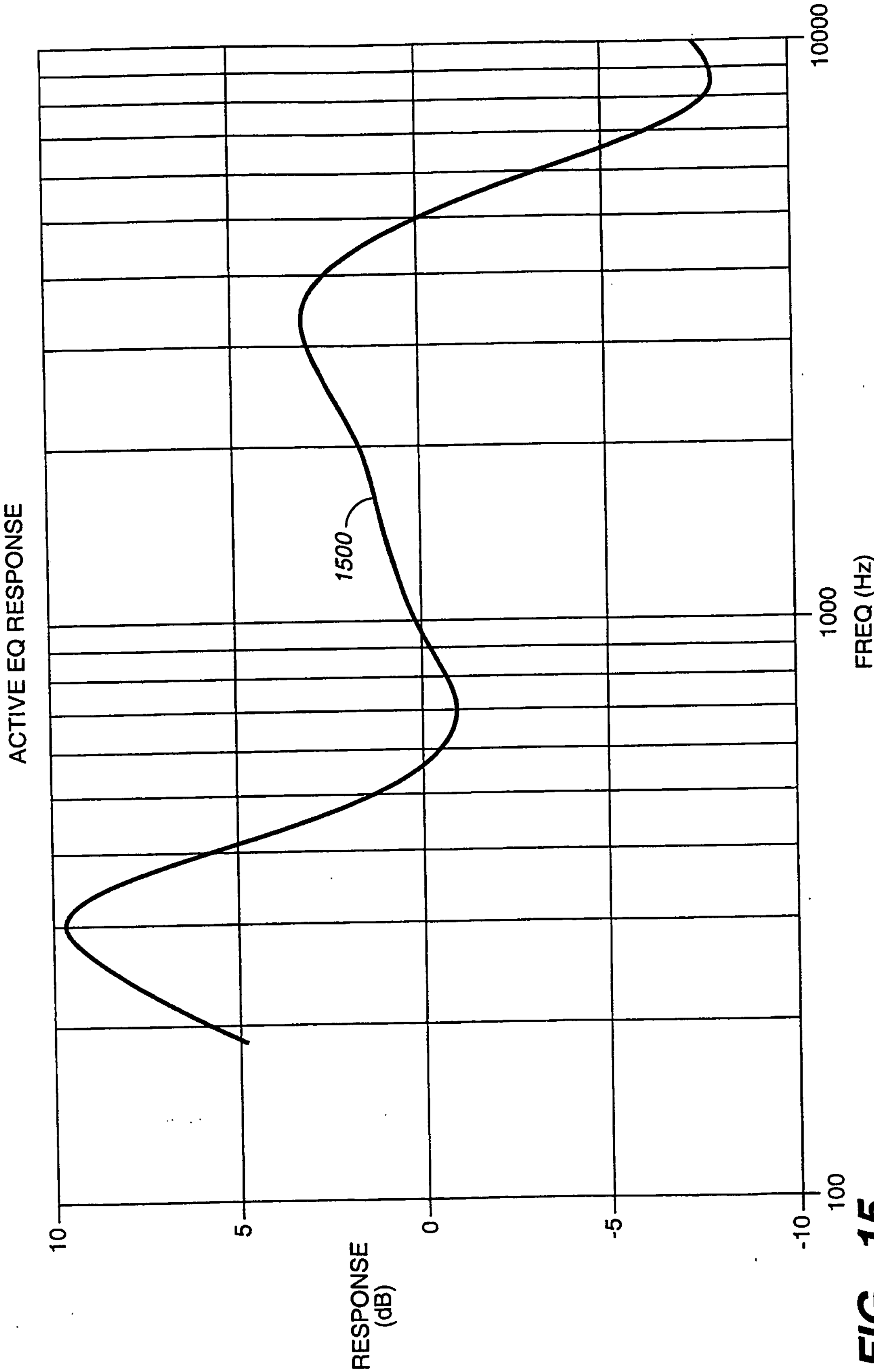

ACTIVE EQ RESPONSE
RESPONSE (dB)
10
5
0
-5
-10
100
1000
10000
FREQ (Hz)
1500

FIG._15

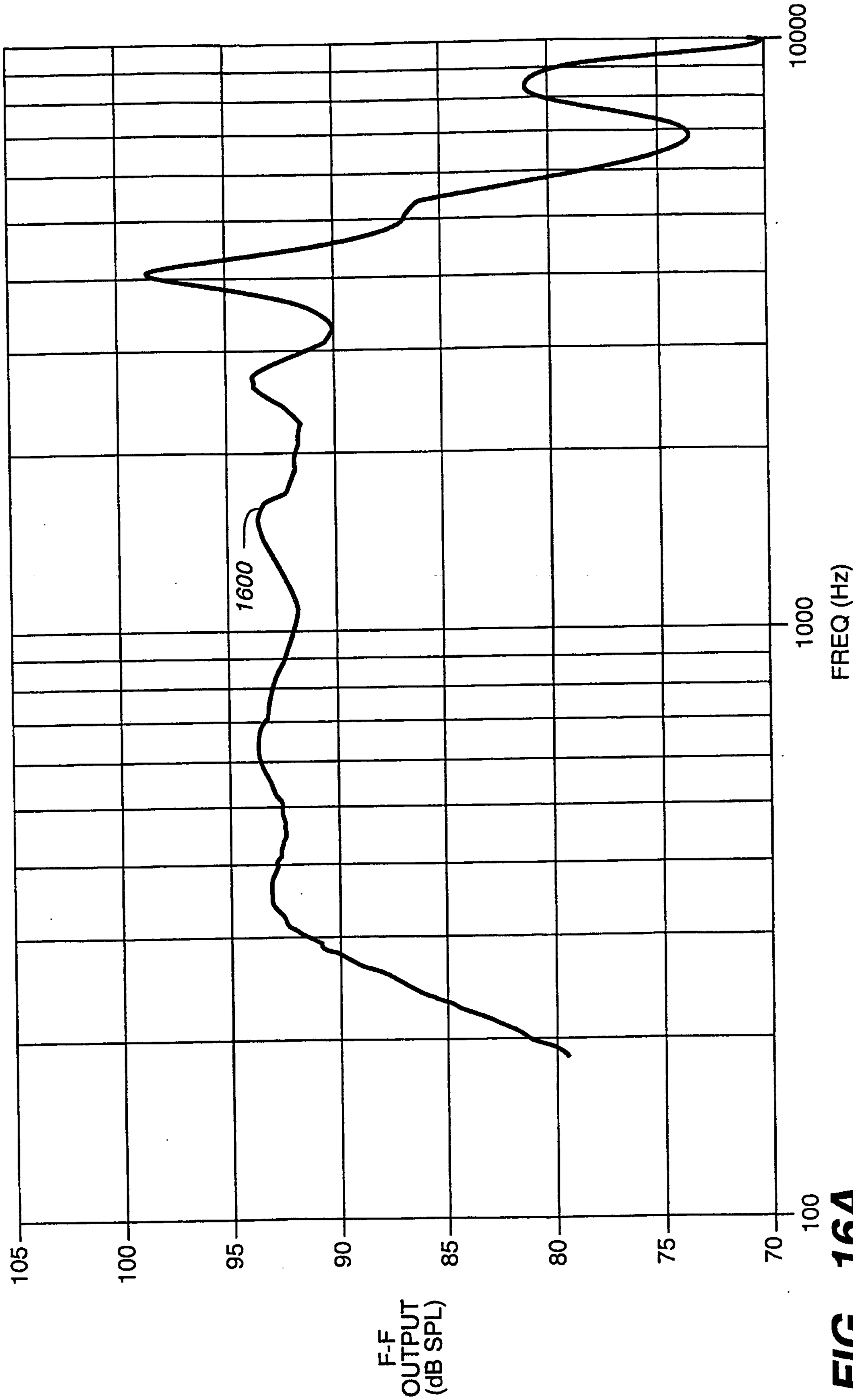

F-F
OUTPUT
(dB SPL)
105
100
95
90
85
80
75
70
100
1000
10000
FREQ (Hz)
1600

FIG._16A

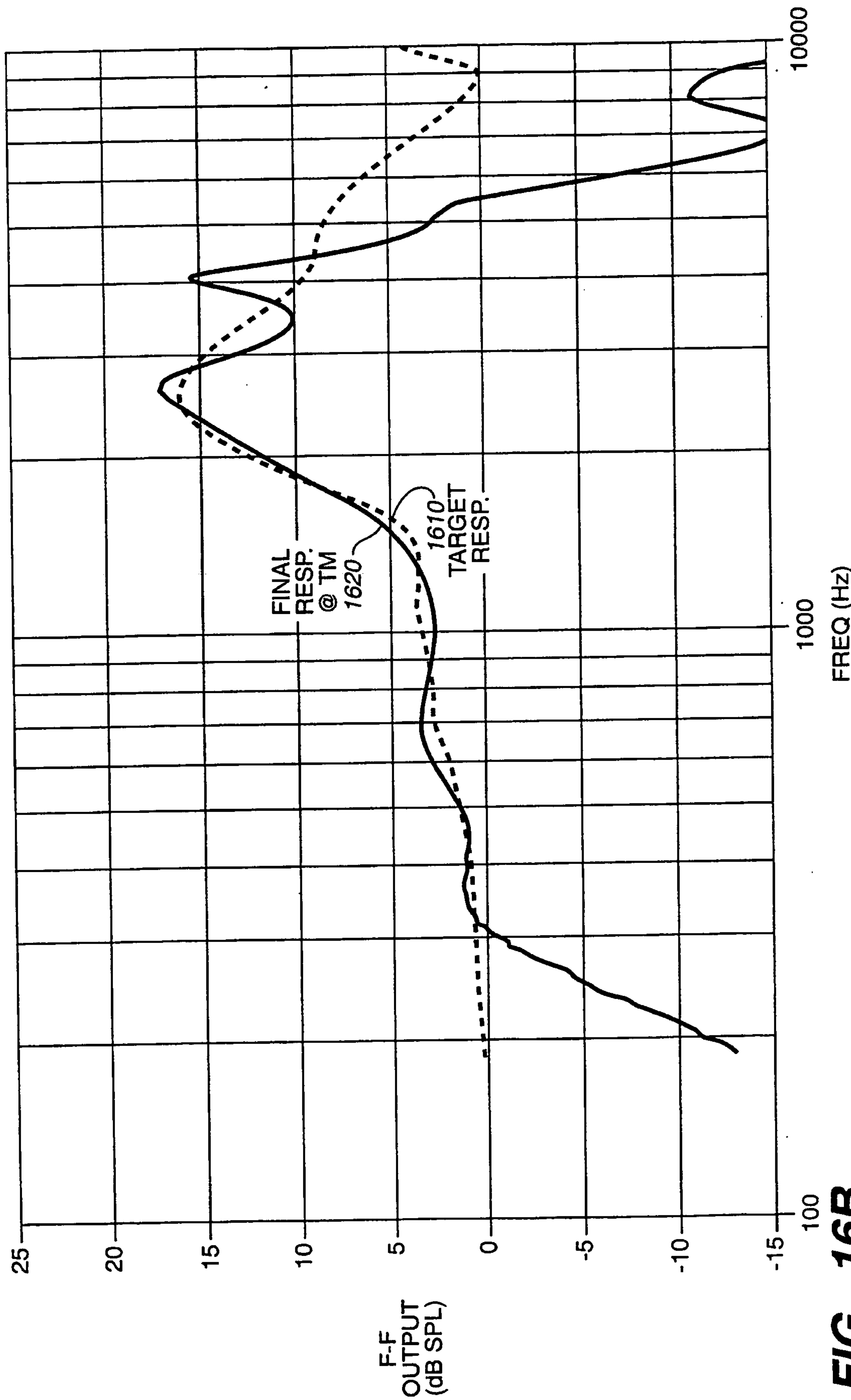

F-F OUTPUT (dB SPL)
25
20
15
10
5
0
-5
-10
-15
100
1000
10000
FREQ (Hz)
FINAL RESP. @ TM
1620
1610
TARGET RESP.

FIG._16B

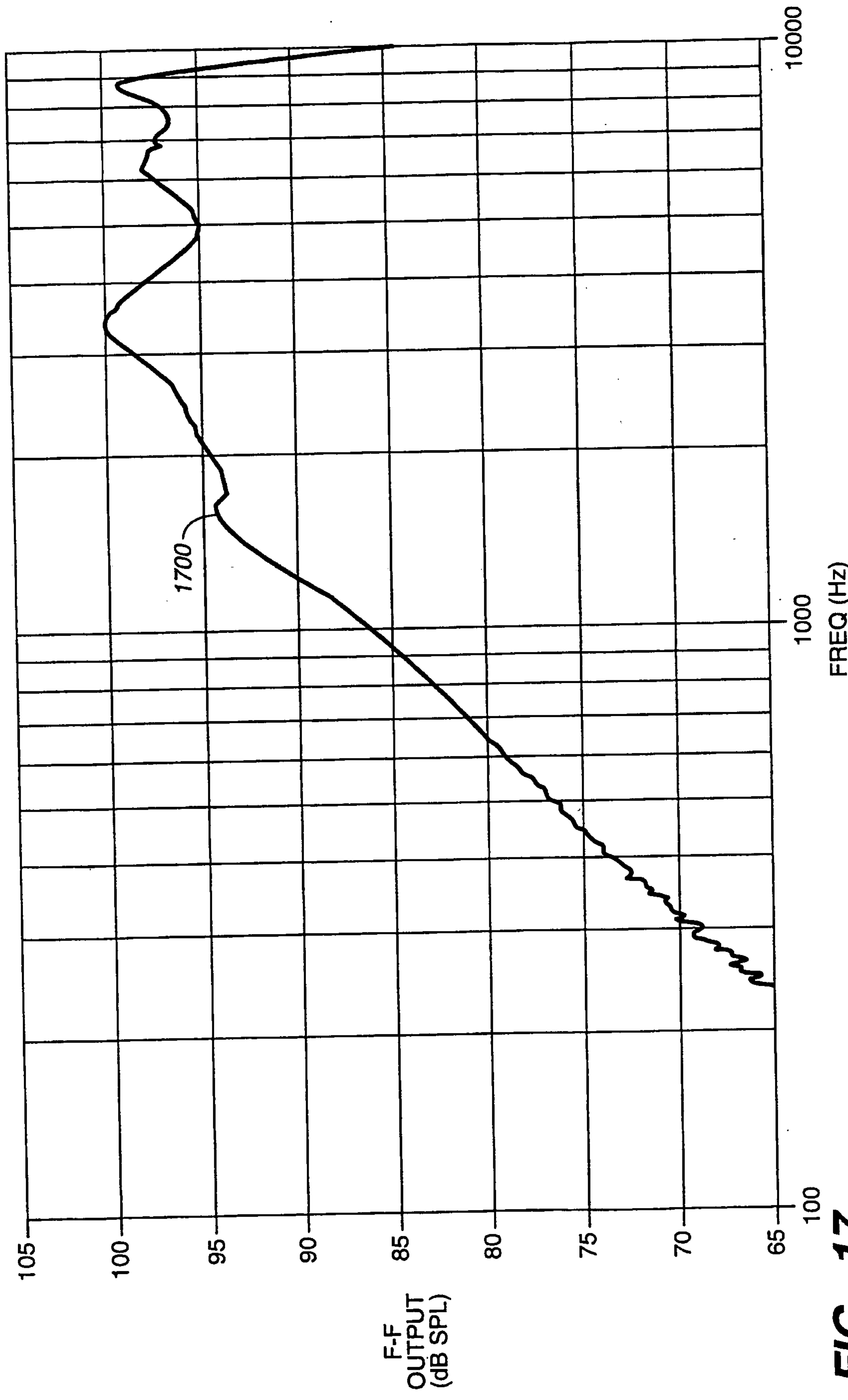

10000
1000
100
FREQ (Hz)
105
100
95
90
85
80
75
70
65
F-F
OUTPUT
(dB SPL)
1700

FIG._17

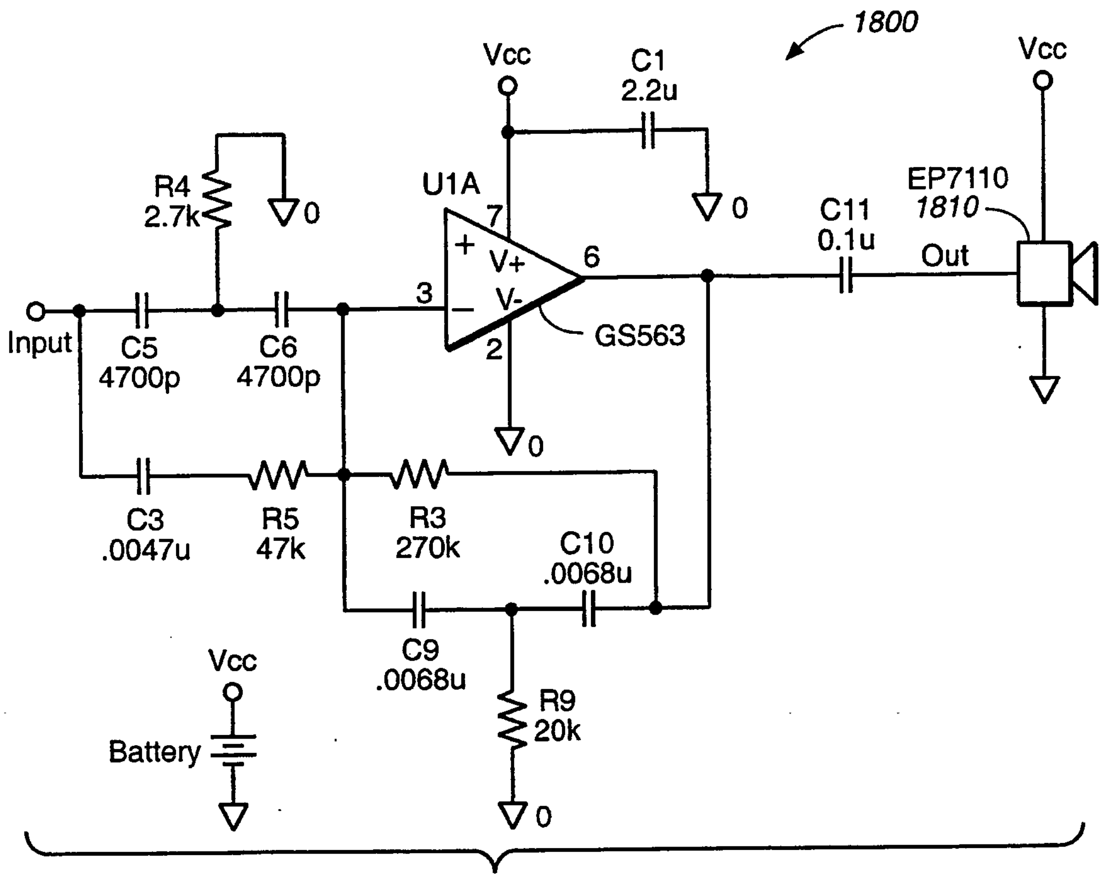


FIG._18

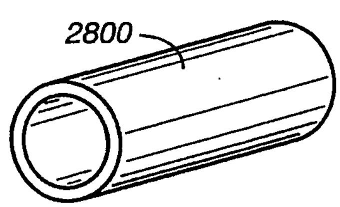


FIG._28

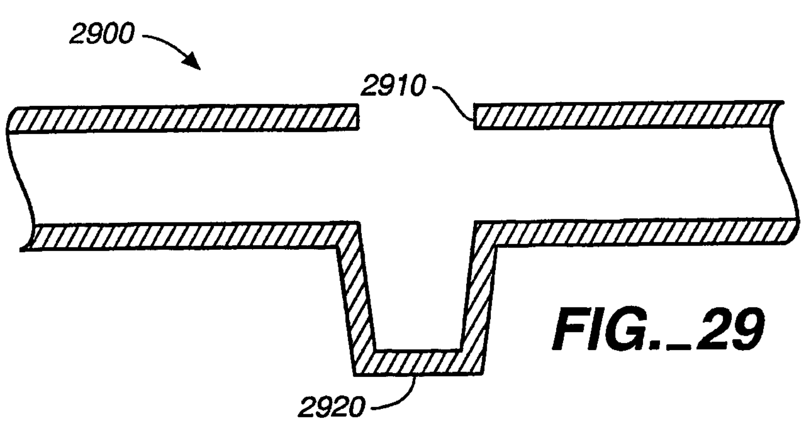


FIG._29

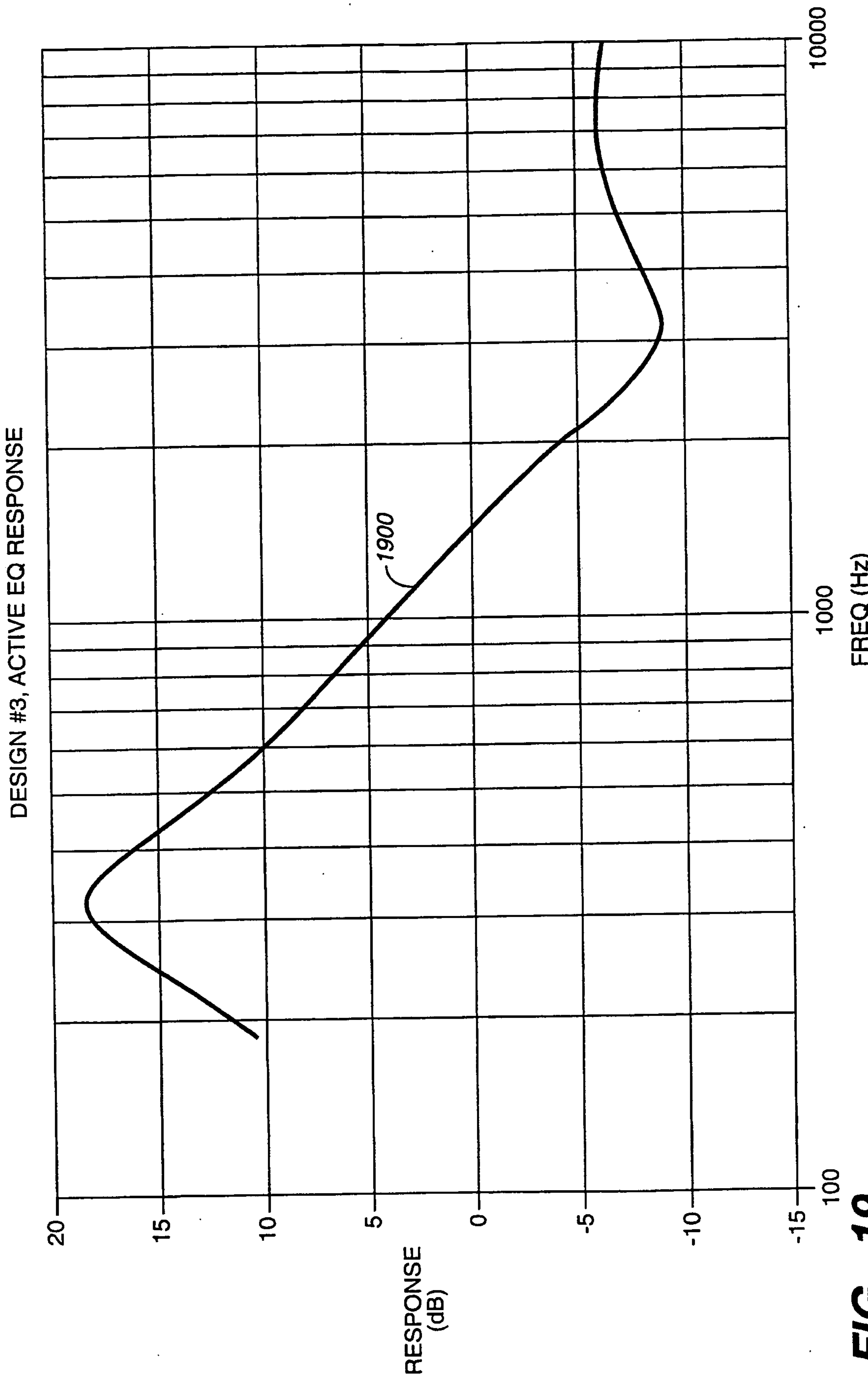

DESIGN #3, ACTIVE EQ RESPONSE
1900
RESPONSE
(dB)
20
15
10
5
0
-5
-10
-15
100
1000
10000
FREQ (Hz)

FIG._19

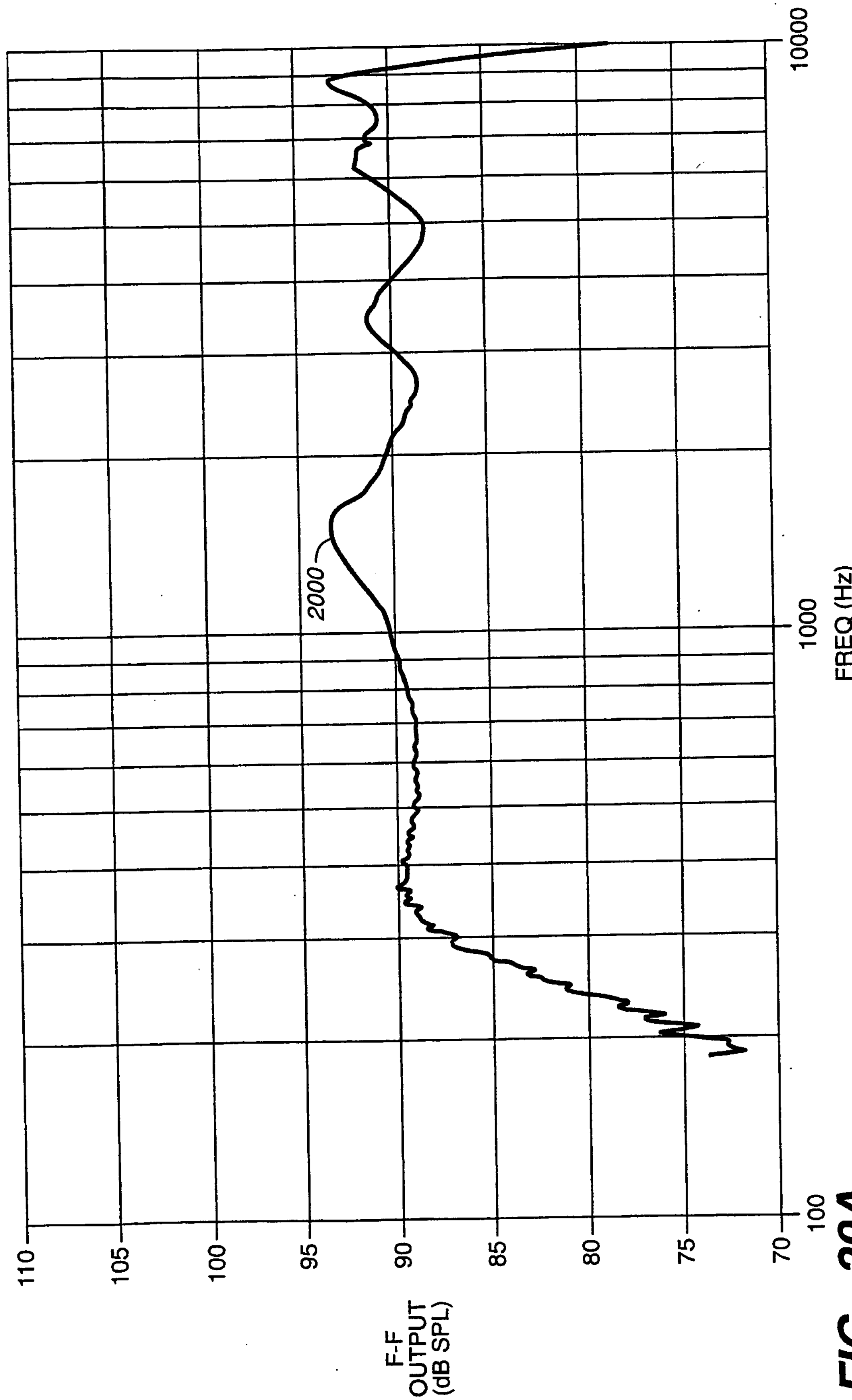

F-F
OUTPUT
(dB SPL)
110
105
100
95
90
85
80
75
70
100
1000
10000
FREQ (Hz)
2000

FIG._20A

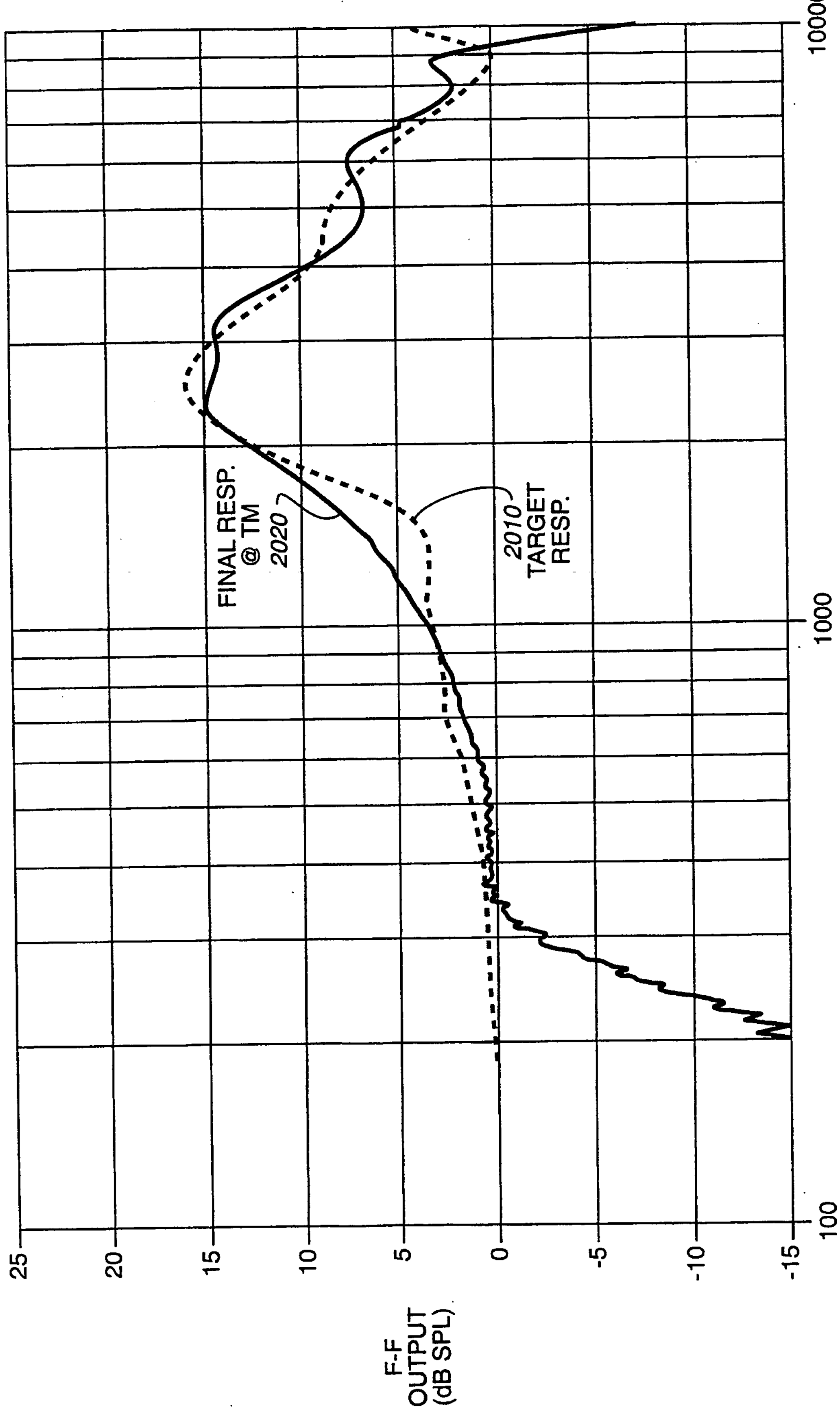

25
20
15
10
5
0
-5
-10
-15
100
1000
10000
FREQ (Hz)
F-F
OUTPUT
(dB SPL)
FINAL RESP.
@ TM
2020
2010
TARGET
RESP.

FIG._20B

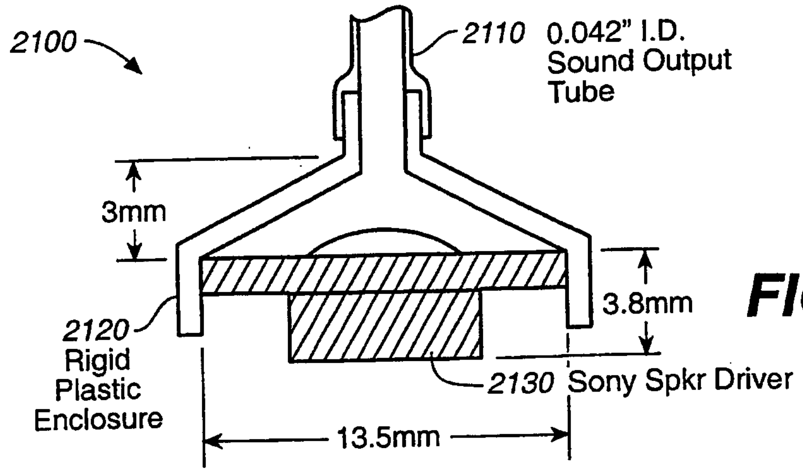


FIG._21

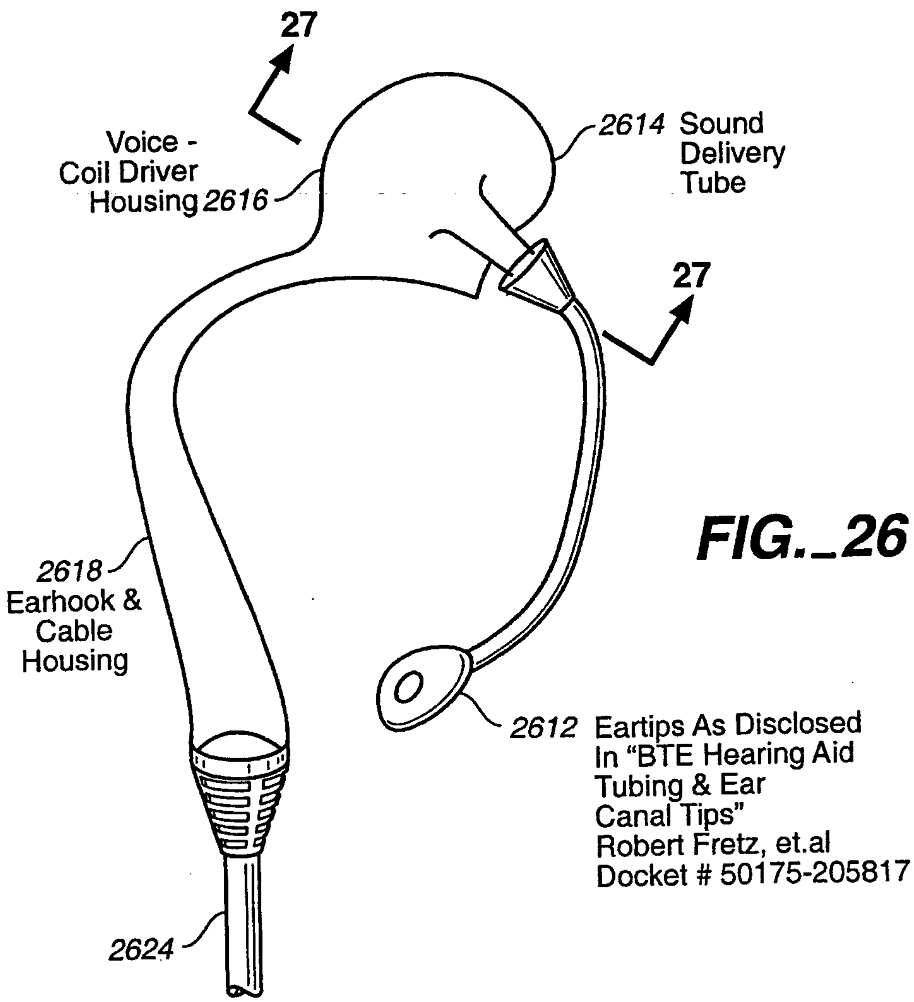


FIG._26

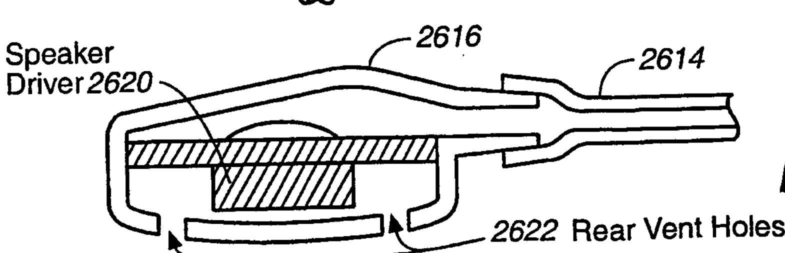


FIG._27

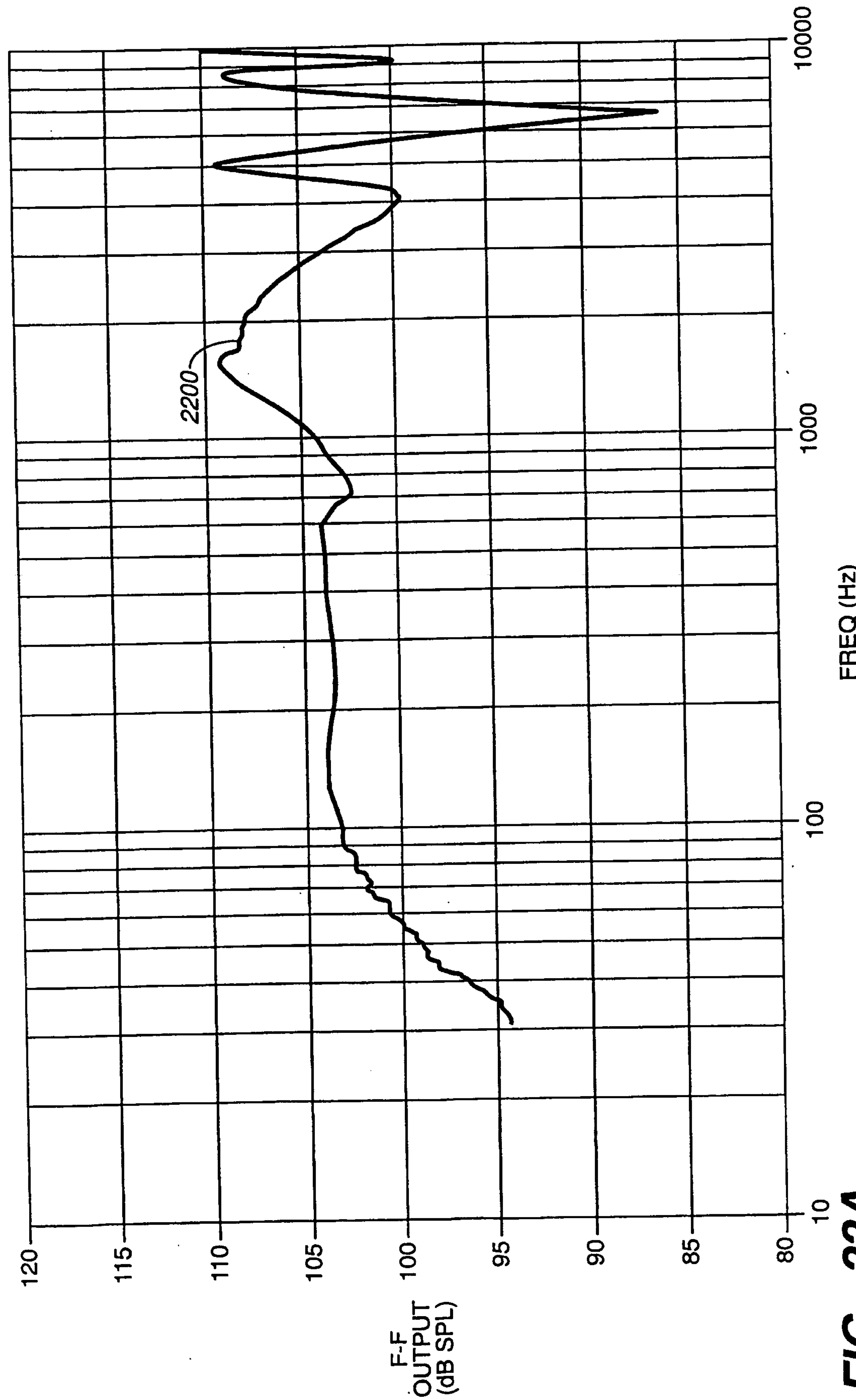

F-F
OUTPUT
(dB SPL)
120
115
110
105
100
95
90
85
80
10
100
1000
10000
FREQ (Hz)
2200

FIG._22A

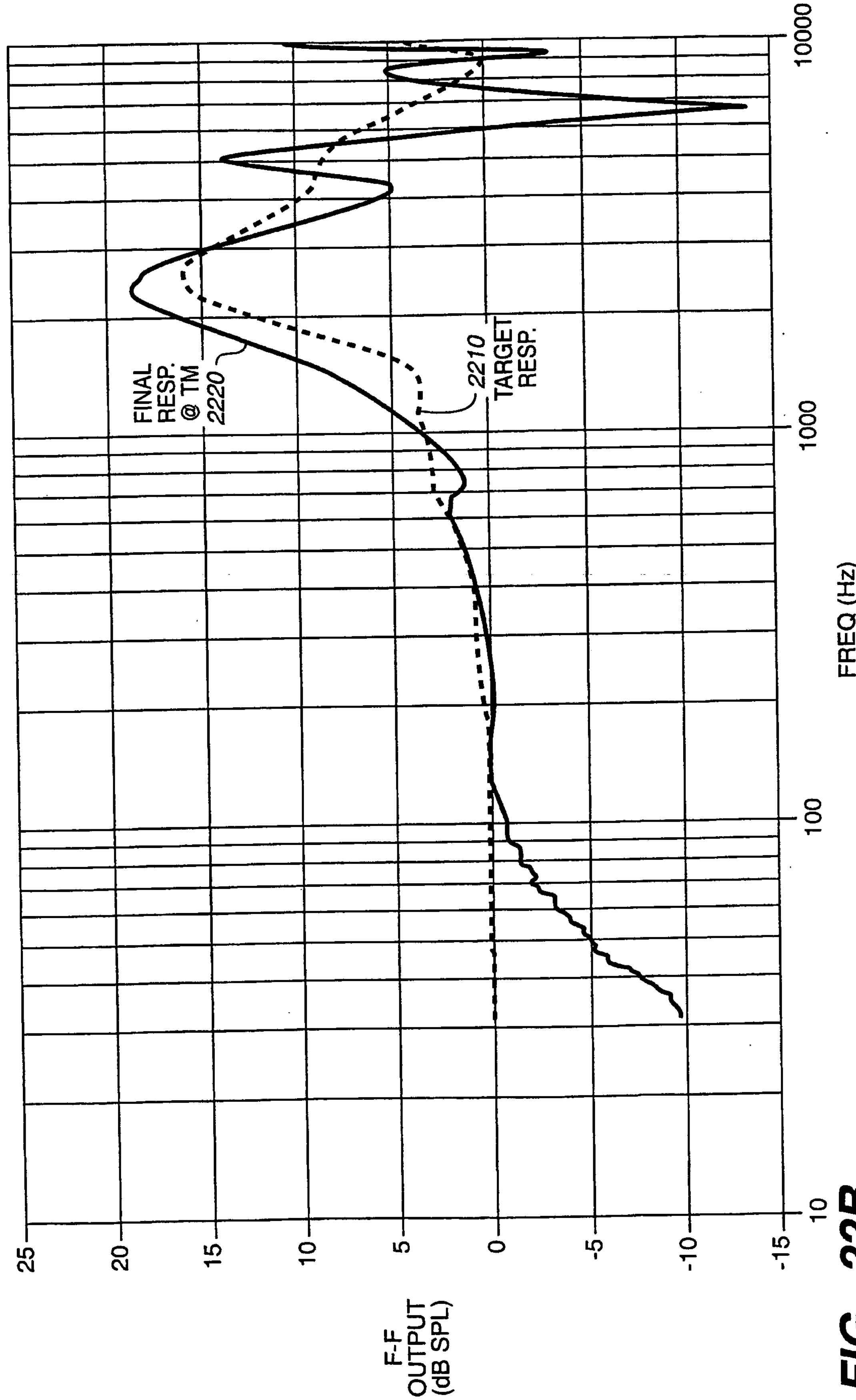

FINAL
RESP.
@ TM
2220
2210
TARGET
RESP.
FREQ (Hz)
10
100
1000
10000
F-F
OUTPUT
(dB SPL)
25
20
15
10
5
0
-5
-10
-15

FIG._22B

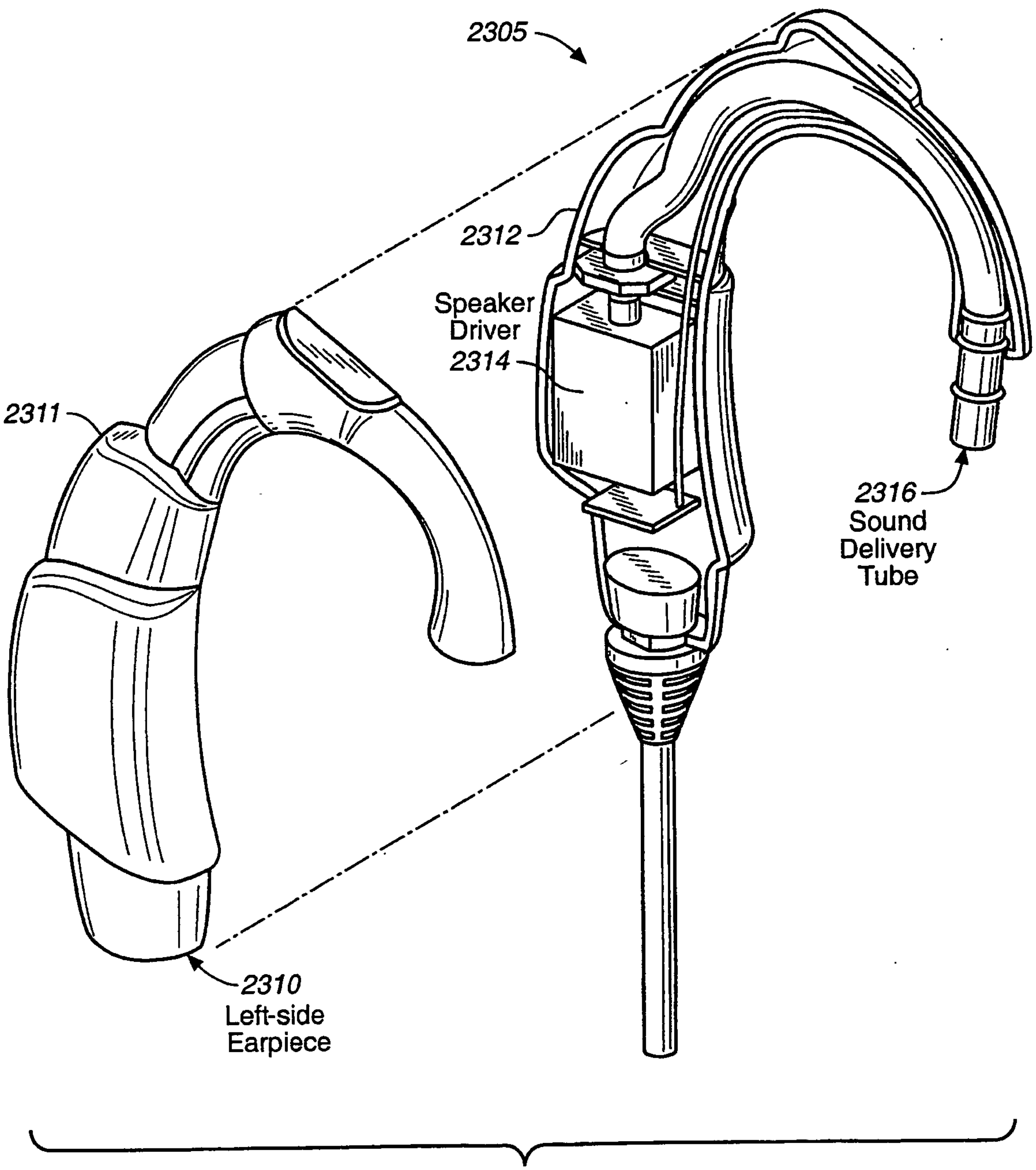

2305
2312
Speaker
Driver
2314
2311
2316
Sound
Delivery
Tube
2310
Left-side
Earpiece

FIG._23A

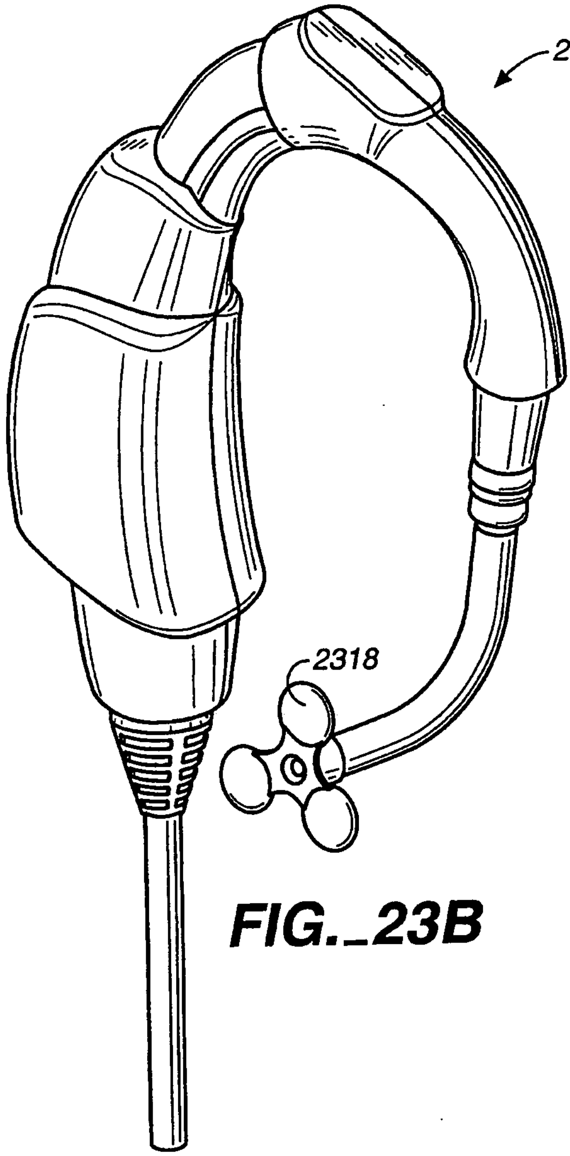


FIG._23B

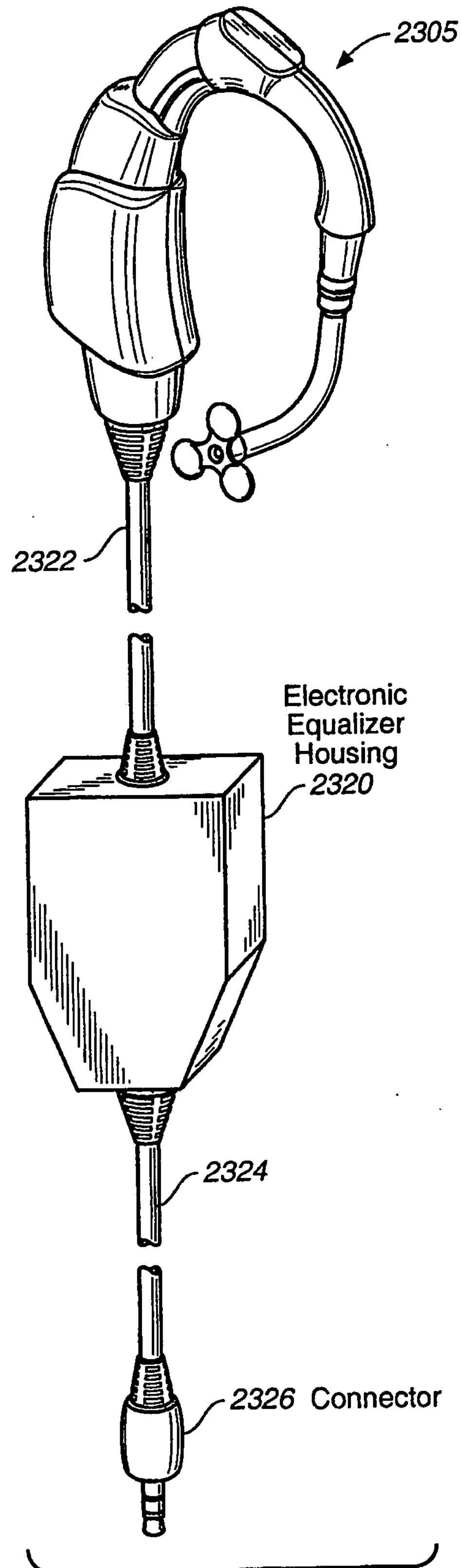


FIG._23C

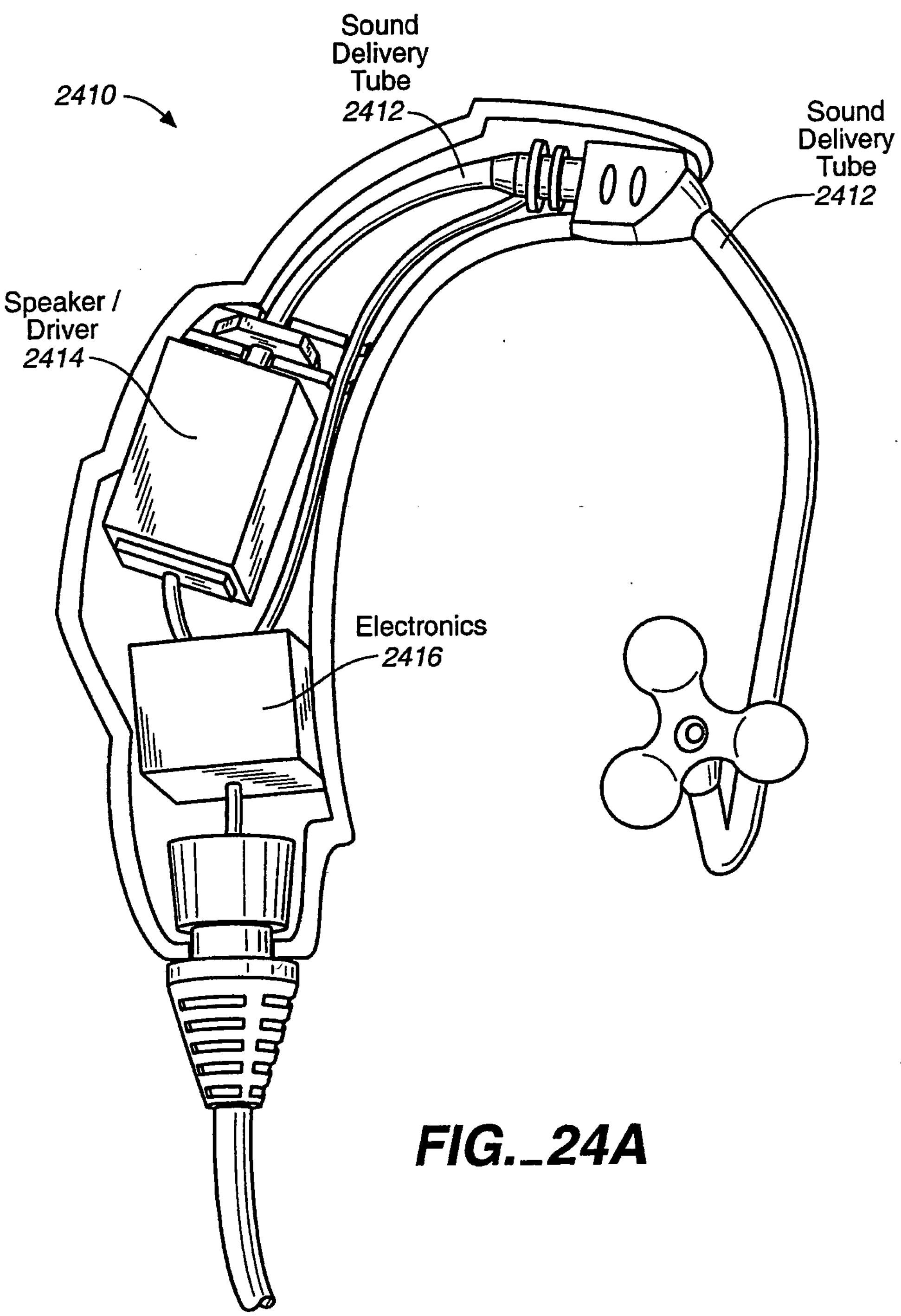

2410
Sound
Delivery
Tube
2412
Sound
Delivery
Tube
2412
Speaker /
Driver
2414
Electronics
2416

FIG._24A

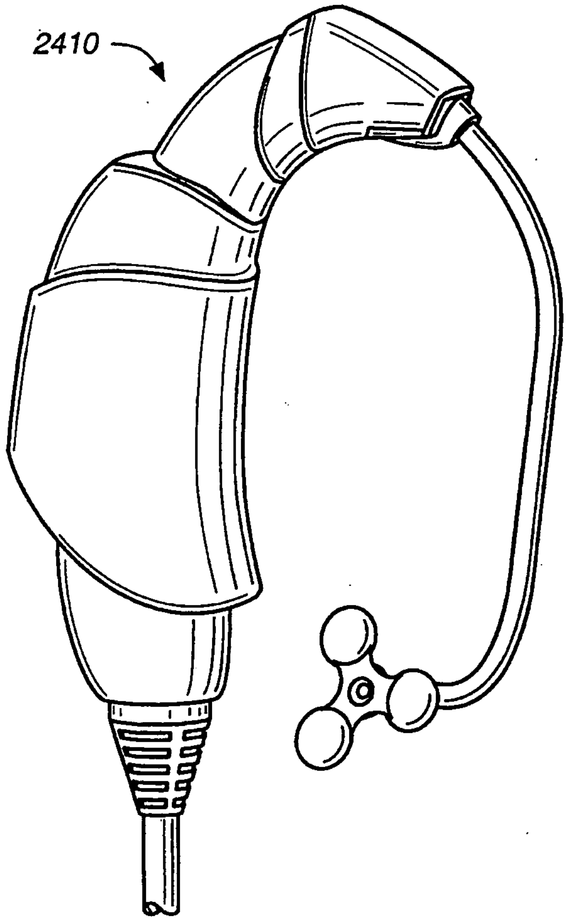


FIG._24B

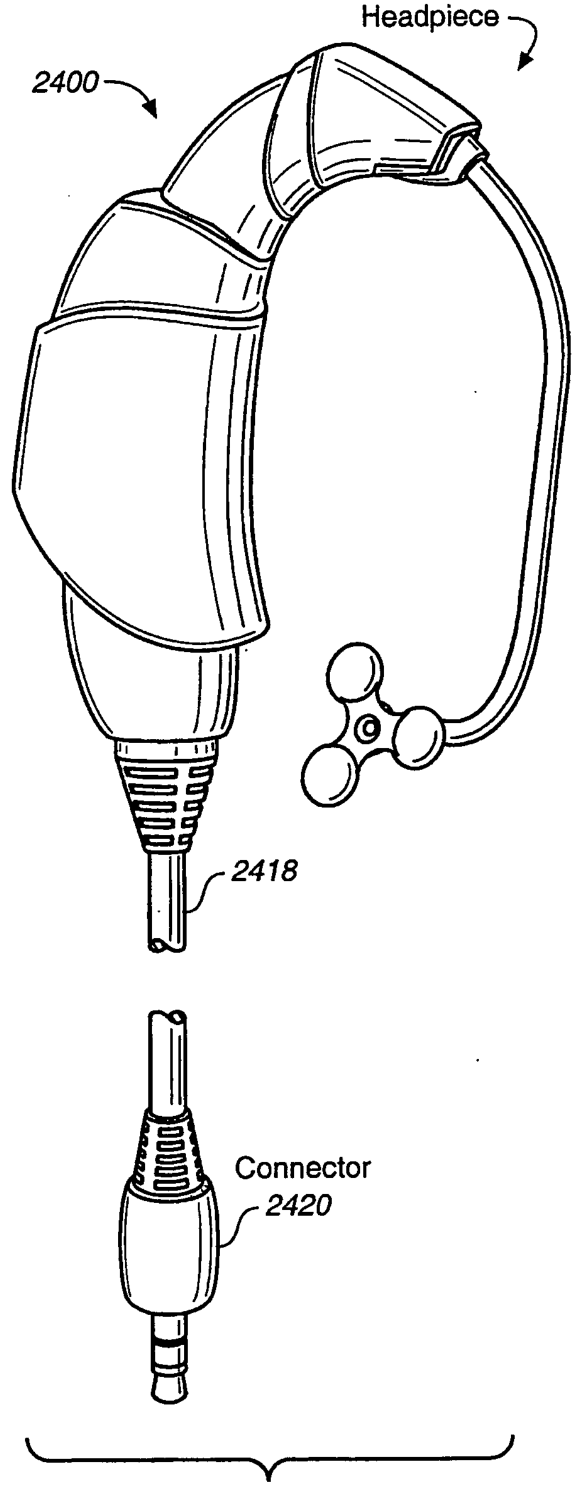


FIG._24C

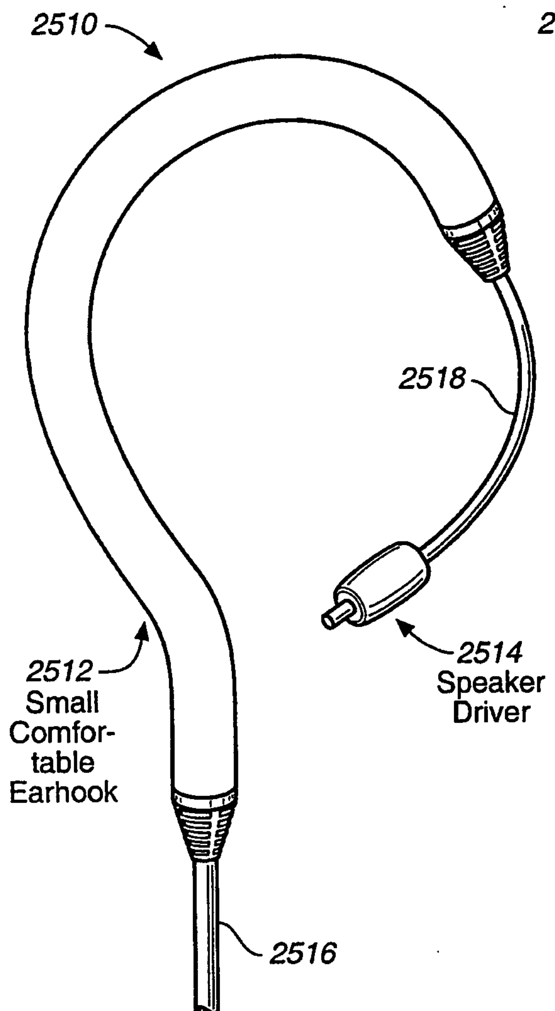


FIG._25A

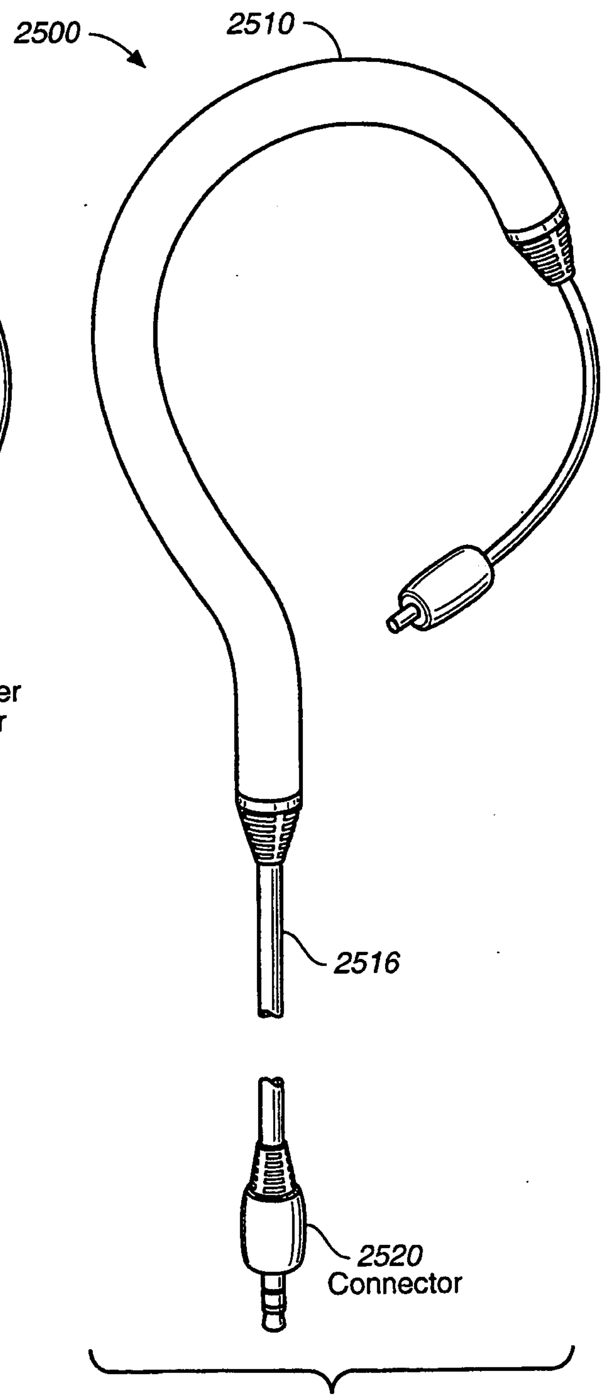


FIG._25B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/12806

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H04R 1/10, 25/00
US CL :381/74, 321
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 381/74, 321, 320, 327, 330, 312, 60

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,729,612 A (ABEL et al) 17 March 1998.	1-34
A,P	US 5,825,894 A (SHENNIB) 20 October 1998.	1-34
A	US 4,677,679 A (KILLION) 30 June 1987.	1-34

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 AUGUST 1999	18 OCT 1999

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	PING LEE Joni Hill
Facsimile No. (703) 305-3230	Telephone No. (703)305-3900